From Linear Lock-in to Circular Default

Ex-Ante Policy Evaluation to Incentivise Circular Construction of Dutch Public Buildings through Residual Value

MADE Thesis

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TU Delft | WUR | Arcadis

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Ex-Ante Policy Evaluation to Incentivise Circular Construction of Dutch Public Buildings through Residual Value

by

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Preface

This thesis marks the final stage of my studies and the MSc Metropolitan Analysis, Design and Engineering (MADE) programme at the AMS Institute. I started the MADE programme with the intention of directing my studies more explicitly towards sustainability and circularity. During the programme, I developed a broader understanding of sustainability, including its environmental, social, and technical dimensions, and how these intersect in complex urban systems. I became more interested in the economic dimension of these challenges, where I believe significant opportunities exist to create value while reducing environmental impact. Writing this thesis has been a challenging but valuable process, through which I learned a lot about the different fields within circular construction. The interdisciplinary nature of MADE has been very valuable in shaping my perspective.

This thesis provided the opportunity to combine the technical and policy foundation of my bachelor's degree in Systems Engineering, Policy Analysis and Management at TU Delft with the interdisciplinary perspective developed during the MSc Metropolitan Analysis, Design and Engineering programme at TU Delft and Wageningen University. I particularly valued the environment at the Marineterrein and the AMS Institute, where the interdisciplinary setting and collaboration with students from diverse backgrounds made working on complex urban challenges inspiring and enjoyable.

I would like to thank my first supervisor, Theodoros, for his guidance and for engaging in discussions on what was, at times, a relatively new subject and evolving research direction. His willingness to spar on ideas and think along throughout the process was invaluable in shaping this work. I also thank my second supervisor, Karel van den Berghe, for his guidance throughout the project.

This thesis was carried out during my time at Arcadis, which provided valuable data, practical insights, and expert knowledge. Thank you to André Hekma for introducing me to this topic and for the opportunity to work on it in a professional setting. I also want to thank Noreen Wesseling for her involvement throughout the process. And, last but not least, I would also like to thank my colleagues at Arcadis for creating an enjoyable working environment.

Another thank you goes to all participants who contributed their time and insights through the interviews. Their perspectives played an important role in grounding this research and challenging its assumptions. Finally, I would like to thank my fellow students, friends, and family for their support and for keeping things in perspective along the way.

To the reader, I hope you enjoy reading this thesis. I am always happy to answer questions or to have a conversation about this work or any related topic.

Rosa Storm
Delft, July 2026

Abstract

Building on the possibility of applying circular depreciation within the Dutch BBV accounting framework, this thesis examines to what extent, and through which mechanisms, policy instruments affect the residual reuse value of Dutch public buildings in order to incentivise circular construction. Methodologically, the study combines literature review, policy document analysis, structured expert elicitation, and scenario and sensitivity analysis. Based on the literature review and policy document analysis identifying economic and governmental barriers to circular construction, three instruments are selected: a labour tax reduction, carbon pricing, and a detachability threshold. Two case studies, an office building and a primary school, are examined across four structural configurations representing conventional, detachable conventional, and bio-based materials. The results show that price-based instruments -labour tax reduction and carbon pricing- increase residual value by lowering the costs of material recovery and reuse, with labour tax having the strongest overall effect, and carbon pricing becoming the stronger lever for carbon-intensive materials such as steel and concrete once detachability is improved. The regulatory instrument -a detachability threshold- determines whether residual value can be realised at all, acting as a precondition for recoverability and reuse. Circular construction is therefore most effectively incentivised through price-based instruments with regulatory requirements ensuring recoverability. The findings and research mechanisms suggest circular construction can be incentivised by increasing the economic viability of bio-based materials and the design of conventional materials for disassembly.

Summary

The construction sector sits at the intersection of resource depletion and climate change, continuing to default to virgin materials where bio-based and secondary alternatives could be used instead. Under Dutch conditions, bio-based and detachable materials often remain financially disadvantaged, and the value embedded in building materials at end-of-life is often not recognised. The research departs from a concrete policy opportunity: the possibility of circular depreciation within the BBV accounting framework. Circular depreciation is an accounting method that reflects the extended lifespan of an asset through reuse, repair, or remanufacturing. Instead of depreciating a building to zero, public building commissioners can recognise residual value, reducing its value to what its materials are worth at end-of-life. Residual value is the theoretical reuse value of a building product at end-of-life, obtained by deducting a set of correction factors from the material value, namely loss, quality reduction, and the costs of detachment, revision, transport, and storage. It is expressed in two forms: an absolute monetary value, and a relative ratio expressing residual value as a share of initial investment costs.

The research is guided by the main question: *to what extent, and through which mechanisms, do policy instruments affect the residual reuse value of Dutch public buildings, and how can this incentivise circular construction?* This question is operationalised through four sub-questions addressing (1) barriers and enablers in the literature, (2) mechanisms reproducing the linear default in Dutch policy, (3) the selection of suitable policy instruments, and (4) quantified effects of selected policy instruments on residual value.

A literature review identifies economic and governmental barriers and enablers to circular construction. The economic barriers identified are the structural under-pricing of virgin materials, the high relative cost of labour-intensive circular activities such as disassembly and remanufacturing, and the near-total invisibility of material value in prevailing valuation frameworks; the governmental barriers identified are the absence of any binding requirement or strong incentive for design for disassembly, and fiscal distortions combined with weak public financial support. The decisive enabling insight is that these barriers are not fixed structural conditions but institutional design choices that can be reconfigured through targeted policy. A policy document analysis then traces how the linear default is produced in the Dutch context: comparing three Dutch policy documents shows that it persists not because instruments are absent, but because existing instruments are targeted to limit linear harm rather than to reward circular value.

To address the identified circular construction barriers, three policy instruments are selected against a twofold criterion: each had to respond to a diagnosed barrier and correspond to a policy-sensitive variable in the residual value methodology, so that it could be operationalised within the model. Two are price-based instruments, a labour tax reduction (lowering the employer social-contribution rate from 21% to 7.4%) and carbon pricing on virgin materials (following PBL's high-delayed trajectory to €540/tonne by 2050), alongside one regulatory instrument, a detachability threshold based on the Design for Disassembly principle and operationalised through the detachability index. The selected policy instruments are customised to fit the adapted theoretical residual value methodology.

The policy instruments are then evaluated through scenario and sensitivity analysis, informed by structured expert elicitation, across two comparative case studies, an office building and a primary school, spanning four structural configurations of conventional, detachable conventional, and bio-based materials. Labour tax reduction emerges as the dominant price-based instrument at present (base) detachability conditions, generating the larger residual-value gain in three of the four structural configurations and acting on two terms of the residual value formula at once: it simultaneously raises the recoverable material share and lowers labour-intensive detachment costs. Carbon pricing contributes positively but more modestly under these conditions, with its strongest gains confined to the heaviest, most carbon-intensive material, a reinforced-concrete floor within the circular design, where it surpasses labour tax before improvement in detachability. Once detachability is improved, however, this ordering in-

verts: carbon pricing becomes the leading price-based instrument for conventional material dominant structures, including the steel structure and the traditional design, while labour tax reduction retains dominant only for the bio-based wood structure. Design for disassembly is shown to be a precondition rather than merely an additional instrument. For conventional material dominant structures, the detachability threshold moves residual value from a substantial write-off to a positive figure. Across both case studies, the policy mix does not alter the relative ordering of structural alternatives: bio-based and already-detachable systems retain their residual-value advantage over conventional steel and traditional designs in every scenario tested. Price-based financial incentives shift the level of outcomes, and determine which instrument leads, within that level, but it is the regulatory standard for detachability that sets the underlying hierarchy of structural alternatives, and increasingly, the base on which the price-based instruments operate at all.

A structured expert elicitation with ten purposively selected practitioners, covering residual value, cost engineering, circular contracting, circular policy design, concrete and steel reuse, circular financing, and municipal real estate, was conducted iteratively throughout the research process to validate scenario plausibility, refine model parameters, and identify blind spots in the model. Overall, experts validated the scenario plausibility and the central transmission logic of the scenario model. Factors including revision and storage costs were identified as sources of uncertainty. Multiple experts noted that the omission of inflation renders the residual value formulation conservative. The sensitivity analysis establishes that the dominant sources of uncertainty within the model are inflation, and detachability and material-quality variables, rather than the policy instrument parameters. This reinforces the thesis's findings: price-based policy instruments operate on the level of residual value outcomes, but material and design characteristics form the base no price-based policy instrument can override.

Finally, the thesis examines how residual value can incentivise circular construction. Once residual value is recognised in the depreciation base, residual value becomes a fiscal instrument in its own right, raising the floor to which a public asset is depreciated. Recognising residual value through circular depreciation is what makes designing with bio-based materials and for detachability financially worthwhile; it rewards the circular design and material choices. Expert interviews suggest municipalities do not take this as a lower annual charge but hold the '*kapitaallasten*' line constant and reallocate the freed room towards monitoring, maintenance, or more circular procurement. The research thus repositions residual value from an end-of-life accounting output into an analytical mechanism, and into broader recognition of residual value as a fiscal policy instrument. The main finding is that policy instruments can raise residual value but cannot, on their own, redefine circular construction: price-based instruments shift the level of value while detachability determines whether it can be realised, and residual value's primary contribution is to make retained material value visible within financial decision-making.

The discussion further situates these findings within the theory of circular construction. Although circularity is a multidimensional concept, this research focuses primarily on its economic and governmental dimensions. Residual value improves financial visibility and viability, but does not fully capture environmental and social value. Moreover, while financial incentives can reshape decision-making conditions, their influence on actual stakeholder behaviour remains uncertain. Price-based instruments shift the level of residual value while detachability determines whether it can be realised at all, and circular configurations consistently retain the most value, suggesting that circularity and sustainability objectives can be aligned rather than traded off. Recommended research directions include bottom-up studies of demolition and on-site practice, broadening the analytical scope beyond the structural layer toward scarce materials such as aluminium, copper, and glass, and extending the single-dimension financial lens with methods that also capture environmental and social value. Taken together, these would move residual value from a promising opening toward a fuller account of what circular construction is worth.

Residual value in circular construction remains an emerging field of study, both in the Netherlands and internationally, and substantial groundwork remains to be established; the findings are therefore best understood as an opening. Conceptually, the research contributes by linking residual value to a policy-mix analysis of conventional and bio-based structural materials within circular construction theory. Methodologically, it contributes by developing and validating an ex-ante scenario model that connects policy instruments to product-level residual reuse value outcomes. Empirically, it provides, to the author's knowledge, the first quantitative assessments of how selected policy instruments affect the residual reuse value of structural materials in Dutch public buildings. Residual value could support the incentivisation of circular construction by making retained material value explicit, enabling more balanced comparisons between circular and conventional materials. As such, it functions less as a measure of circularity and more as a prerequisite, enhancing the economic viability of detachable and bio-based materials over the building life cycle. From a policy perspective, making residual value visible could help address key barriers to circular construction, such as high labour costs for reuse and low prices of virgin materials, by enabling more balanced decision-making. While it does not resolve circular construction barriers directly, it clarifies where additional policy instruments (such as labour tax reduction, carbon pricing, or a detachability threshold) may be most effective, thereby supporting better alignment between financial decision-making and circular construction goals. A valuable step is from theoretical to observed data, to enrich the residual value methodology with empirical data on recovered materials.

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Nomenclature

Abbreviations

Abbreviation	Definition
AMS	Amsterdam Institute for Advanced Metropolitan Solutions
BBV	Besluit Begroting en Verantwoording (Dutch municipal accounting framework)
CB'23	Platform Circulair Bouwen 2023
CE	Circular Economy
CLT	Cross-Laminated Timber
DB	Direct Building Costs
DfD	Design for Disassembly
DI	Detachability Index
EC	Embodied Carbon
EZK	Ministry of Economic Affairs and Climate (Economische Zaken en Klimaat)
Glulam	Glue-Laminated Timber
IenW	Ministry of Infrastructure and Water Management (Infrastructuur en Waterstaat)
KCBR	Kenniscentrum voor Beleid en Regelgeving
L	Loss (of building product after detachment)
MADE	Metropolitan Analysis, Design, and Engineering
NPCE	National Programme Circular Economy
OAT	One-at-a-Time (sensitivity analysis)
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
QR	Quality Reduction
RC	Revision Costs
RV	Residual Value
SC	Storage Costs
TC	Transport Costs
TPM	Technology, Policy & Management (TU Delft faculty)
UNEP	United Nations Environment Programme
WKR	Wetenschappelijke Klimaatraad (Scientific Climate Council)
WUR	Wageningen University & Research

Symbols

Symbol	Definition	Unit
RV	Residual value of the building component	[€]
V_{mat}	Gross material value (before losses and costs)	[€]
DB	Demountable building cost / initial reference cost	[€]
$\%_{\mathrm{mat}}$	Material share of total building value	[–]
L	Material loss during disassembly	[€]
$\%_{\mathrm{loss}}$	Loss fraction as a function of detachability index	[–]
QR	Quality reduction in material value	[€]
$\%_{\mathrm{quality}}$	Quality reduction factor based on condition score (NEN 2767)	[–]
DI	Detachability index	[–]

Symbol	Definition	Unit
cor_{DI}	Detachability correction factor for cost and loss	[–]
DC	Detachment costs	[€]
RC	Revision costs before reuse	[€]
$\%_{\mathrm{rev}}$	Revision percentage applied to evaluate quality reduction	[–]
C_{lab}	Labour cost component	[€/]
$\%_{\mathrm{labour}}$	Labour cost share of DB	[–]
TC	Transport costs	[€]
C_{load}	Loading cost per hour	[€/h]
t_{load}	Loading time	[h]
C_{unload}	Unloading cost per hour	[€/h]
t_{unload}	Unloading time	[h]
w_{ton}	Material weight	[ton]
C_{tonkm}	Transport cost per ton-kilometre	[€/(ton $\cdot km)]$
d	Transport distance	[km]
SC	Storage costs	[€]
C_{indoor}	Indoor storage rate	[€/m^2 · yr]
T_{storage}	Storage duration	[months]
A	Material footprint area	[m^2]
F_{traffic}	Traffic space factor	[–]
F_{stack}	Stacking factor	[–]
t	Age at the time of reuse	[years]
L_{life}	Service life of the component	[years]
C	Condition factor (NEN 2767)	[–]
τ_L	Labour tax (employer social contribution rate)	[%]
$p_{\mathrm{CO_2}}$	Carbon price	[€/tonne]
EC	Embodied carbon intensity	[kg CO_2eq/kg]

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Introduction

The construction and buildings sector sits at the intersection of two planetary crises, accelerating resource depletion and human induced climate change, and is, in both cases, one of the largest sectoral contributors. The following chapter narrows this global crisis to a researchable Dutch-specific research gap.

1.1. Problem Background

In 2020, the buildings and construction sector were responsible for 37% of global energy-related CO_2 emissions and consumed 36% of total global final energy, where the manufacturing of building materials accounted for 10% of global energy-related CO_2 (UNEP, 2023). These are not static figures: rapid urbanisation and population growth continue to drive rising demand for materials in the built environment (Fishman et al., 2016; Wiedenhofer et al., 2019). Global material use is expected to more than double by 2060, with one-third of this rise attributable to construction materials (UNEP, 2023). In 2030, structural steel demand alone is projected to surge by 50% (Ayati et al., 2022).

Intensifying resource depletion and increasing pressure on the Earth's finite natural capital (Jørgensen & Pedersen, 2018) are closely linked to the dominance of the traditional linear economic mode, which is based on a take-make-dispose logic whereby raw materials are extracted, processed into products, and discarded after use (Guerra & Leite, 2021). Before the industrial revolution, the high value of materials relative to labour ensured that buildings and products were maintained, repaired, and upgraded, so that the value embedded in materials was retained over long periods. As post-industrial production lowered the relative cost of materials, that incentive eroded: materials became cheap enough to discard rather than recover, and the retention of their embedded value has since received limited attention in contemporary analysis and policy (Allwood et al., 2011). The construction and building sector is a clear example: because it relies heavily on linear economic systems, it is a major driver of resource depletion (Amarasinghe et al., 2025).

Buildings have become more efficient in operation, shifting emissions toward embodied carbon associated with raw material extraction, transportation, and the processing and manufacturing of building products (Pomponi & Moncaster, 2016, 2018). This calls for approaches that minimise virgin resource use and incentivise reuse with maximised retained value (Jiang et al., 2022). Currently, 57% of construction-material value is lost at end-of-life (McKinsey, 2022) and only 1% of construction components in North-West Europe were reused following first application (Gobbo et al., 2021). Building products are technically reusable, but frequently downcycled, presenting simultaneously an environmental failure as well as an economic inefficiency. This indicates that the problem is not only technical feasibility, but the absence of mechanisms that recognise and retain material value.

In the context of rising material demand and increasing raw material scarcity (Ayati et al., 2022; Fishman et al., 2016; Wiedenhofer et al., 2019), effective circular economy strategies in the construction and buildings sector depend on the repeated use of already extracted resources (Gobbo et al., 2021; McKinsey, 2022) rather than continued reliance on virgin materials. Bio-based and secondary materials typically carry higher upfront costs than virgin alternatives, which remain one of the key factors shaping their adoption (Le et al., 2024). As a result, linear virgin material continues to be the default. The issue, however, is not merely the technical possibility of reuse, but the absence of mechanisms to recognise and capitalise on the economic value embedded in building materials over time. As Linder et al. (2017) and Jiang et al. (2022) observe, current markets provide no reliable information on the economic value embedded in materials within buildings.

1.2. Dutch Context Analysis

In March 2026, the Scientific Climate Council (WKR) published the advisory report *Circulariteit Versterkt* (WKR, 2026), which argues that circular opportunities must be considered more systematically in financing and investment decisions and highlights that the construction and building sector remains strongly oriented towards linear business models and virgin material use. As of now, the Dutch building and construction policy landscape is primarily focussed on CO_2 reduction and the energy transition (KPMG, 2025).

In the Netherlands, where construction is the primary driver of ecological pressure in the country, responsible for 50% of national raw material consumption (Ministerie van Infrastructuur en Waterstaat, 2024), a fundamental tension exists between circular economy ambitions and current political and regulatory reality. Despite the urgency of the 2030 mandate, now less than four years away, the term 'circular' appears only five times in the most recent Dutch coalition agreement (“Regeerakkoord 2026 | Parlement.com,” 2026). The limited circular ambition that does appear centres on a wish to 'create a level playing field and dismantle regulatory and economic bottlenecks'. The National Programme Circular Economy 2025 critically reflects on its own approach, stating: 'circular economy policy has focused primarily on a voluntary, noncommittal approach (Rijksoverheid, 2023). As long as price signals favour linear practices, they must change for the Dutch government to meet its circular ambitions (Rijksoverheid, 2023).

1.3. Opportunity Statement

The opportunity lies in the Dutch accounting framework for public authorities, the BBV (Besluit begroting en verantwoording), which allows for circular depreciation. Within this framework, public building commissioners can recognise the residual reuse value of building materials. Instead of depreciating assets to zero, circular depreciation retains value based on the recoverable reuse value of materials at end-of-life. The residual value methodology developed by Alba Concepts and bbn adviseurs, operationalised through the Revalto tool in collaboration with Arcadis, provides a building product-level calculation framework for residual reuse value. In June 2025, this methodology was approved by the BBV Committee. The residual value methodology was initiated by Invest-NL within the Educational Housing Programme (POHV), in collaboration with the Ministry of Education, Culture and Science, the VNG, PO-Raad, and VO-Raad.

This is relevant for the present thesis because public buildings fall within the accounting treatment of tangible fixed assets, meaning that incorporation of residual value operates within the BBV framework. This governs how such assets can be recognised, depreciated, and reported on municipal balance sheets. By making residual value verifiable and auditable, it enables the establishment of circular value in a manner that can be incorporated and presents a *financial opportunity*. Traditional depreciation reduces a building’s value to zero over its lifetime, assuming it is worth nothing at the end. Circular depreciation only reduces the value down to what the building’s materials are still worth, since those materials can be reused, remanufactured, or resold.

A visual illustration of traditional depreciation and circular depreciation is illustrated below:

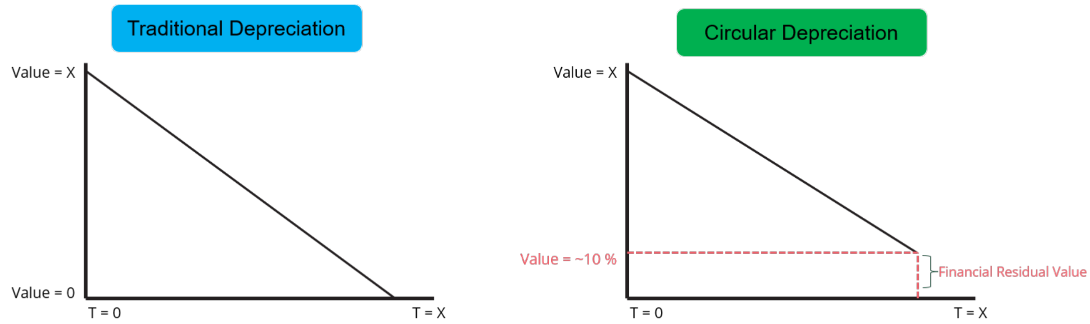

Figure 1.1: Visualisation of linear and circular depreciation for a scenario with financial residual value equal to 10% of the initial investment.

This opportunity represents more than an accounting adjustment. It creates a lever through which public building commissioners can begin to recognise, retain, and mobilise value embedded in buildings. Circular depreciation and the residual value methodology provide a stepping stone for incentivising circular construction and the use of more circular materials, making the value of materials visible, rather than leaving it as an environmental ambition alone. This creates the conditions under which material value can influence financial decision-making, which is central to this thesis. At the time of writing (*June 2026*), *eleven* municipalities have incorporated financial residual value into their Nota Activabeleid, consistent with Article 212 of the Municipalities Act and the BBV accounting framework.

1.4. Research and Policy Gap

Recognising material value forms the analytical core of this research and responds to the limited body of literature on residual value (Jiang et al., 2022). The environmental impacts of the construction sector are well established, however both policy and academic research have predominantly focused on operational energy use and CO_2 emissions (D'Amico & Pomponi, 2020; Pomponi & Moncaster, 2016). In the Dutch context, this is reflected in policy priorities centred on the energy transition and emission reduction (KPMG, 2025), leaving the economic value embedded in materials largely unaddressed. In a context of rising material demand and increasing raw material scarcity (Ayati et al., 2022; Fishman et al., 2016; Wiedenhofer et al., 2019), effective circular economy strategies in the construction sector depend on the repeated use of already extracted resources (Gobbo et al., 2021; McKinsey, 2022), yet bio-based and secondary materials often carry higher upfront costs than virgin alternatives (Le et al., 2024). As a result, virgin material use remains the default, not because circular alternatives are technically infeasible, but because their retained value is not recognised in financial decision-making.

This reveals a clear *policy gap*. Despite ambitious circular economy targets, current instruments are primarily oriented toward reducing linear harm rather than actively rewarding circular value. Material reuse and bio-based alternatives therefore receive limited direct financial incentives, and the value retained in building materials at end-of-life remains largely invisible. A corresponding *research gap* exists in the literature. Existing studies on circular construction predominantly assess environmental performance, often through life-cycle assessment, while economic dimensions remain comparatively underdeveloped (Keena et al., 2022). Although design for disassembly is shown to reduce embodied environmental impacts (Mouton et al., 2022), its implications for economic value retention and financial decision-making are rarely quantified. In addition, qualitative studies identify a broader set of barriers and enablers to circular and bio-based construction, including institutional inertia, fragmented supply chains, lack of standardisation, and limited market maturity (Le et al., 2024). However, these insights remain largely disconnected from quantitative assessments of financial value.

As a result, there is limited understanding of how material valuation interacts with policy instruments and how this relationship influences financing and investment decisions in practice. This constitutes the central *research gap*: the relationship between material valuation, policy instruments, and incentivisation of circular construction remains insufficiently understood. This research addresses both the policy and research gap by quantifying how policy instruments, as financial incentives, affect the residual reuse value of conventional and bio-based building materials. In doing so, it connects qualitative barrier analysis with quantitative valuation, and examines how material valuation can make embedded value visible and actionable within the Dutch institutional context of Article 212 of the *Gemeentewet* and the BBV accounting framework, thereby contributing to the economic viability and adoption of circular construction in public buildings.

The contribution is threefold:

- *Empirically*, there is little evidence on the residual value of building materials and how it responds to policy instruments in the Dutch public-building sector.
- *Conceptually*, current research insufficiently links circular construction principles to financial valuation frameworks, limiting their integration into investment decisions and policy design.
- *Methodologically*, few ex-ante, model-based analyses simulate how policy instruments affect circular outcomes. Few studies provide quantitative scenario and sensitivity analysis, linking policy design to financial and economic outcomes at the building level.

This thesis provides, to the author's knowledge, the first such analysis, combining literature and policy review, scenario and sensitivity analysis, and structured expert elicitation to test whether selected policy instruments can contribute to shifting the financial logic of circular construction in a Dutch context.

1.5. Research Scope, Aim and Questions

The aim of this research is to analyse how policy can incentivise circular construction of public buildings as a more economically and financially rational default under Dutch conditions, by quantifying how policy instruments affect the residual reuse value of building product materials.

The research scope focuses on three structural material typologies, reinforced concrete, structural steel, and engineered wood, which are analysed because these represent the dominant material choices in Dutch construction and exhibit different profiles with respect to residual value variables. They are selected to compare bio-based and conventional Dutch structural building material typologies. Three policy instruments are selected for further analysis because they intervene at different points where circular construction is currently priced out. A policy mix analysis on carbon pricing and labour tax, as well as a regulatory design standard for detachability on the theoretical residual value are explored.

The primary intended users of the research findings are the Ministry of Economic Affairs and Climate (EZK), the Ministry of Infrastructure and Water Management (IenW), and public building commissioners such as municipalities. At the same time, the thesis remains relevant to a broader range of stakeholders across the construction and building sector, including designers, contractors, valuation experts, financiers, and circular-economy intermediaries. The findings on the analysed policy instruments and material valuation can be informative beyond the public domain alone. The research is guided by the following main research question and four supporting sub-questions:

Main Research Question

To what extent, and through which mechanisms, do policy instruments affect the residual reuse value of Dutch public buildings, and how can this incentivise circular construction?

Sub-Questions

The main question is operationalised through four sub-questions, each addressing a different layer of the problem.

SQ1. *What economic and governmental barriers and enablers to circular construction are identified in academic literature?*

SQ2. *What economic and governmental mechanisms produce the 'linear default' for Dutch public buildings?*

SQ3. *Which policy instruments are most suitable for incentivising residual reuse value, given the identified barriers and the variables of theoretical residual value?*

SQ4. *To what extent do price-based instruments (a labour tax reduction and carbon pricing) and the regulatory instrument (a detachability threshold) affect residual reuse value—individually, relative to one another, and in combination?*

1.6. Research Design

To answer the research questions, This thesis adopts an ex-ante policy evaluation as its overarching research design. Ex-ante is a Latin term meaning “before the event”. Ex-ante analysis is used prospectively to inform policy decisions by estimating a policy’s likely impact on a research objective before it is implemented (Lee, 2025). The ex-ante policy evaluation combines a mixed-method approach which is structured in two phases.

Phase I identifies enablers and barriers to circular construction and the mechanisms producing a linear default in the Netherlands, to select candidate policy instruments, informed by a literature review and policy document analysis. Phase II evaluates these instruments, through a policy-mix analysis, informed iteratively through expert elicitation, and scenario and sensitivity analysis, The residual reuse value methodology is used as the central evaluative lens. This design allows the thesis to move from problem diagnosis and incentive selection to an ex-ante assessment of how policy instruments affect the residual reuse value of building product materials of Dutch public buildings. The methodological design is set out in full in Chapter 3.

The design is justified rather than assumed, on three grounds: the question is interdisciplinary, spanning institutional barriers, public policy, circular construction, and financial valuation, so it needs triangulation; the topic is data-limited and future-oriented, so structured expert elicitation is a necessary complement; and the ex-ante orientation fits a thesis that aims to assess instruments that do not yet exist in the form modelled.

The primary unit of analysis is the financial residual reuse value of load-bearing building components in Dutch public buildings. This unit is central because the thesis seeks to understand whether policy instruments can alter the value retention of structural materials at end-of-life. The focus on load-bearing structures is analytically justified by their high material mass, cost significance, and embodied carbon relevance (D’Amico & Pomponi, 2020), which together make them decisive for both environmental impact and financial residual value. The analytical unit is structured hierarchically: from the residual value of public buildings within the BBV accounting framework, to the load-bearing structure, to its key building products (floor slabs, beams, and columns), and ultimately to the comparison between bio-based and conventional materials, namely reinforced concrete, structural steel, and engineered wood.

The research design is iterative rather than linear. Although the thesis is organised in sequential chapters, the underlying methodological process moved back and forth between literature (grey and academic), scenario analysis, and expert elicitation. This iterative character is important because the study addresses an emerging topic in which the relevant variables, plausible policy mechanisms, and case-study boundaries could not be fully fixed in advance. Instead, the design developed through structured feedback loops in which each phase refined the next and, where necessary, prompted revisions of earlier assumptions. Early informal practitioner conversations were used as bounded scoping input to sharpen the focus on structural materials, load-bearing systems, and the most relevant incentive mechanisms.

1.7. Research Relevance

The research aims to make distinct societal and scientific contributions listed in the following paragraph:

Societal Relevance This research addresses the implementation gap between Dutch national circular economy targets, namely a 50% reduction in primary resource use by 2030 and full circularity by 2050, and the current policy framework. Despite ambitious targets, existing instruments insufficiently incentivise material reuse in practice.

The findings aim to provide actionable insights for the Ministry of Economic Affairs and Climate Policy (EZK) and for public clients commissioning new buildings, supporting effective policy design that aligns policy instruments with the policy compass and circular construction goals.

Scientific Relevance This research advances the academic debate by moving beyond qualitative identification of economic and governmental barriers toward their quantification. Rather than merely stating that current policies undervalue building materials, this study demonstrates the magnitude of this undervaluation and evaluates how different policy instruments can reduce it.

The research makes key contributions:

- It extends the literature on governmental and economic barriers and enablers to circular construction by introducing a quantitative, financially grounded perspective.
- It responds to calls for methodological advancement by applying scenario-based modelling to simulate policies specifically allocated for material reuse.
- It integrates expert perspectives with modelling results, demonstrating that policy effectiveness depends not only on instrument design but also on the broader institutional context.

Relation to the MSc Metropolitan Analysis, Design, and Engineering Program

Within the field of Metropolitan Analysis, Design, and Engineering (MADE), or the broader field of circularity in the built environment and sustainable urban development, this research addresses the intersection of circular construction and policy design. It links circular construction practices to policy frameworks, addressing a core challenge in sustainable urban development: aligning environmental objectives with economic feasibility.

The research focuses on incentivising circular value, rather than focussing on isolated technical solutions, emphasising the role of institutions, instruments, and governance in shaping material flows within cities

The government's dual role, as both regulator and commissioner of public buildings, offers a distinct opportunity to influence the economic viability of circular construction. Finally, the research responds to a recurring tension I encountered during classroom discussions in both my bachelor's (Technology, Policy Management at TU Delft) and master's studies: circular and sustainable solutions are often technically feasible, yet their implementation is frequently constrained by financial viability, which tends to drive decisions, especially in the built environment.

1.8. Thesis Structure

This thesis is structured in nine chapters that move from problem and opportunity analysis, through conceptual and methodological development, to analysis and reflection. Two phases, selection of policy instrument (phase I) and evaluation of policy instruments (Phase II), structure the results.

Chapter 1 introduces the research problem, the blind spot in current Dutch circular construction policy, and sets out the research questions and overall aim. Chapter 2 develops the theoretical background, establishing the concepts of residual value, circular construction, and the structural materials that form the units of analysis. Chapter 3 presents the methodological design, detailing the mixed-methods approach, the residual value modelling strategy, and the role of expert elicitation. The empirical core of the thesis then proceeds in four steps.

Phase I: Selection of Policy Instruments Chapter 4 analyses the barriers, enablers, and mechanisms that shape the adoption of circular construction. Building on this, Chapter 5 sets out the selection of policy instruments most relevant to the identified barriers and to residual value.

Phase II: Evaluation of Policy Instruments Chapter 6 operationalises these instruments into a model-ready scenario framework, translating labour tax reduction, carbon pricing, and the detachability threshold into model variables and case-study inputs. Chapter 7 then evaluates the instruments through the scenario analysis, comparing their individual and combined effects on residual value across structural and material configurations.

The final two chapters interpret and position the findings of the research. Chapter 8 discusses the results in relation to theory and the wider literature, and reflects on the contribution, implications, research limitations, and methodological choices of the study. The chapter ends by identifying future research directions. Chapter 9 concludes by answering the research questions and offering recommendations derived from the research findings.

2
Theoretical Background

This chapter establishes the conceptual and theoretical background the thesis builds on, in three steps. Section 2.1 defines circular construction, positions the thesis within an established research framework, and sets out the relevant concepts for Dutch public buildings. Section 2.2 develops the concept of residual value and how it is operationalised. Section 2.3 narrows the scope to the load-bearing structure and its materials.

2.1. Circular Construction of Dutch Public Buildings

2.1.1. A Governmental and Economic Perspective on Circular Construction

This study adopts the definition of circular construction proposed by (Ossio et al., 2023) for two main reasons. First, the construction industry currently lacks a clear and unified definition of the concept, which risks the misapplication of circular economy principles in the built environment. Second, this definition is derived from a systematic literature review of 316 publications and is grounded in nine attributes drawn from five clusters of conceptual affinities, giving it a robust, evidence-based foundation rather than a purely theoretical one. *Circular construction* can be defined as “a multidimensional and dynamic economic system for construction based on the application of Circular Economy principles. It aims to achieve buildings and infrastructure designs considering different systemic levels (micro, meso, and macro) to achieve a built environment that targets zero waste and pollution. It allows construction materials and products to remain in use, retaining their maximum value by following biological or technical looping strategies through and within the whole life cycle of construction projects. This approach operates in a sustainable, clean, and renewable way, allowing for the regeneration of natural systems. It is enabled by a context defined by technology, management systems, government policies and regulations, business models, and social and stakeholder behavior that enable construction needs to be met sustainably”.

Circular construction is a multidimensional concept, spanning technological, environmental, societal, behavioural, and governmental and economic domains (Pomponi & Moncaster, 2017). These dimensions are interdependent: the technical capacity to disassemble and reuse a component means little if no actor has a financial reason to do so, and an environmental case for reuse does not, on its own, alter an investment decision. This thesis is positioned primarily within the governmental and economic dimensions of that framework, while recognising the others as the context within which these dimensions operate.

2.1.2. Concepts and Definitions of Circular Construction in the Netherlands

To clarify the analytical scope of this thesis, the levels-of-scale framework adopted from the Platform CB’23 *Lexicon Circulaire Bouw* (Platform CB’23, 2024) distinguishes between the different scales embedded within the built environment. A level of scale (*schaalniveau*) is defined as the subdivision of a construction work, and sometimes its surroundings, into logical units on the basis of size and/or function. This distinction matters because the thesis does not assess residual value at the level of the building as an undifferentiated whole, but traces it through the load-bearing structure, the construction products that compose that structure, and the underlying material basis from which those products are made. The relevant scales, from the building as the overarching asset down to the raw material, are summarised in Table 2.1.

Table 2.1: Levels-of-scale relevant to the analytical scope of this thesis (definitions adapted from Platform CB'23

Level of scale	Definition
Building	A constructed or to-be-constructed work, composed of elements and/or construction products, that forms a single whole and serves a specific function (e.g. a residential building, school, hangar, viaduct, transmission tower, switching station, or railway).
Element	An abstract part of a construction work distinguished solely on the basis of a desired function — for example, spatial separation, load-bearing structure, lighting, heating, or security. The load-bearing structure is the element that forms the analytical focus of this thesis.
Building product	A product manufactured or processed for incorporation into construction works, built up from one or more materials (e.g. bricks, ready-mix concrete, windows, switches, boilers). In prefabrication, products are manufactured into elements before delivery to the site.
Material	A natural or artificially produced substance intended to be processed into a product.
Raw material	A crude, unprocessed substance that can be converted into a material, for example, iron ore processed into iron.

Beyond the levels of scale, a small set of circular concepts recurs throughout the analysis. These terms define the material strategies and value dimensions through which residual value is assessed, and are used here in the sense established by the Platform CB'23 lexicon (Platform CB'23, 2024). They are summarised in Table 2.2.

The circular concepts used in this thesis are interwoven through material value: value retention focuses on reuse over recycling, which preserves the residual value embedded in structural materials at end-of-life, and is made technically possible by detachability and design for disassembly. This logic is material-specific: circular materials are operationalised as either conventional detachable materials within the technical cycle (reinforced concrete and structural steel) or bio-based materials within the biological cycle (engineered wood), so that residual value becomes the measurable expression of how well each material typology retains reusable value.

Table 2.2: Key circular concepts used in this thesis (definitions adapted from Platform CB'23)

Concept	Definition
Bio-based material	A material derived entirely from biomass. bio-based materials are renewable and form part of the biological cycle.
Detachability (*losmaakbaarheid*)	The degree to which an object can be taken apart non-destructively at all levels of scale, without compromising the function of the object or surrounding objects, thereby preserving existing value. Detachability is a key technical driver of residual value in the model.
Design for disassembly	Designing an object so that it can be taken apart simply and without damage, and reassembled equally simply — in Dutch terms *demonteren* / *remontabel*.
Technical cycle	The cycle in which products, components, and materials are restored so that they can be used again as new products, components, and materials. Conventional structural materials such as concrete and steel belong to this cycle, as distinct from the biological cycle of bio-based materials.
Reuse	Using objects again in the same function. Reuse is the highest-value R-principle targeted by the residual value approach, as distinct from recycling (recovering materials to make new products).
Value retention (*waardebehoud*)	Retention of functional-technical and/or economic value by extending lifespan or by retaining objects and their raw materials at the end of the life cycle at the highest possible functionality.
Circular material	A circular material refers to a material whose design and application enable the retention of its functional, technical, and economic value across multiple life cycles. This is achieved through strategies that facilitate high-value reuse, such as design for disassembly (detachability) and the use of renewable or bio-based inputs, thereby supporting the continued circulation of material resources at their highest utility.

Circular construction in this thesis can be understood to depend on feasibility (technical), viability (economic), visibility (informational). Feasibility refers to the technical capacity of building systems and materials to be reused, for example through design for disassembly and (bio-based/conventional) material performance. Viability captures whether circular options are financially and economically attractive compared to linear alternatives, which can ultimately determine their uptake in construction. Visibility concerns the extent to which the value of materials, particularly their residual reuse value, is measurable, recognised, and incorporated into decision-making processes.

2.1.3. Circular Construction Criteria in the Netherlands

Within a Dutch context, the framework *Het Nieuwe Normaal* (HNN) translates the broad concept of circular construction into a more operational set of performance criteria. HNN structures circular construction around three interconnected domains: environmental impact, material use, and value preservation. Together, these domains clarify that circular construction is not limited to reducing emissions or selecting better materials, but also concerns whether buildings are designed in ways that preserve value, disassembly potential, and future reuse. This is particularly relevant for the present thesis, because the value-preservation domain aligns most directly with the question of how policy and financial instruments can increase the residual reuse value of structural materials in public buildings.

Environmental impact. In HNN, circular construction includes designing and constructing buildings with the lowest possible environmental cost, as expressed through the *Milieuprestatie Gebouw* (MPG), the lowest possible embodied carbon in line with Paris Proof ambitions, and the highest possible level of carbon storage in construction materials.

Material use. HNN also emphasises responsible material sourcing, prioritising bio-based, reused, and recycled materials wherever feasible, while encouraging the use of healthy materials and the reduction of residual construction waste. In this way, material use is not assessed only in terms of quantity, but also in terms of origin, health, and circular resource flows.

Value preservation. HNN's emphasis on value preservation, where buildings should be designed with the highest possible degree of adaptability, disassembly potential, and reuse potential. These criteria are especially important because they shift attention from one-off material consumption to the long-term capacity of building products and components to retain economic and functional value over multiple use cycles. In this sense, HNN provides a practical interpretation of circular construction that reinforces the argument of this thesis: circularity becomes meaningful when buildings are not only lower-impact, but also materially recoverable and financially legible at end-of-life.

2.2. Quantifying A Building's Product Residual Reuse Value

2.2.1. Definition of Residual Value

Residual value is the theoretical reuse value of a product after deduction of the main value-diminishing factors that occur between first use and a subsequent use cycle. As markets provide no reliable information on the economic value embedded in materials within existing buildings (Jiang et al., 2022; Linder et al., 2017), the theoretical residual value is validated as the strongest analytical core of residual value.

'Residual Value' (RV) in this research is defined as *the theoretical reuse value of a building product.* Residual value, also known as 'salvage value' or ' future value', refers to the estimated worth of an asset at the end of its useful life. It is therefore a *projected* value rather than an observed market outcome.

In this research, residual value is operationalised in two complementary forms. First, it is expressed as an *absolute monetary value* (in €), representing the economic value that can be recovered from a building product. This value explicitly incorporates both positive and negative cash flows: revenues from material recovery constitute positive flows, while losses and costs constitute negative flows.

Second, residual value is expressed as a *relative percentage* of the initial costs. This relative indicator captures the proportion of value that is retained at the end-of-life (EoL) stage, enabling comparison across materials and scenarios and it is the base for circular depreciation As commonly applied in valuation practice, residual value may be represented as either an absolute monetary amount or as a percentage of the initial investment (Jiang et al., 2022).

Within the context of circular construction, residual value is defined as the remaining value of a building component at the moment of demolition or deconstruction, reflecting its potential for reuse rather than disposal. Although residual value is not a standalone indicator of circularity (Jiang et al., 2022), its quantification is a necessary condition for integrating material reuse into financial decision-making. Despite its importance, the literature on residual value in the built environment remains limited and characterised by considerable uncertainty (Jiang et al., 2022).

2.2.2. Operationalization of Residual Reuse Value in the Netherlands

The most operationally detailed and institutionally validated residual value tool currently available for Dutch buildings, is the Revalto software tool launched last year, which is adopted as the primary quantitative instrument. It utilises the residual value methodology, commissioned by Invest-NL within the Educational Housing Programme (Alba Concepts et al., 2025), and provides construction cost data from Arcadis building cost data (BDB) alongside circularity measurement from the BCI Gebouw platform (BCI Gebouw, 2025). Residual reuse value is the value of a building product at end-of-life, obtained by deducting a set of correction factors from the material value, namely loss, quality reduction, and the costs of detachment, revision, transport, and storage. It is expressed in two forms: an absolute monetary value, and a relative ratio expressing residual value as a share of initial investment costs. The calculations that form the base of the starting material value and the correction factors can be found in Appendix A.

A visual representation of how residual reuse value is established can be seen in figure 2.1:

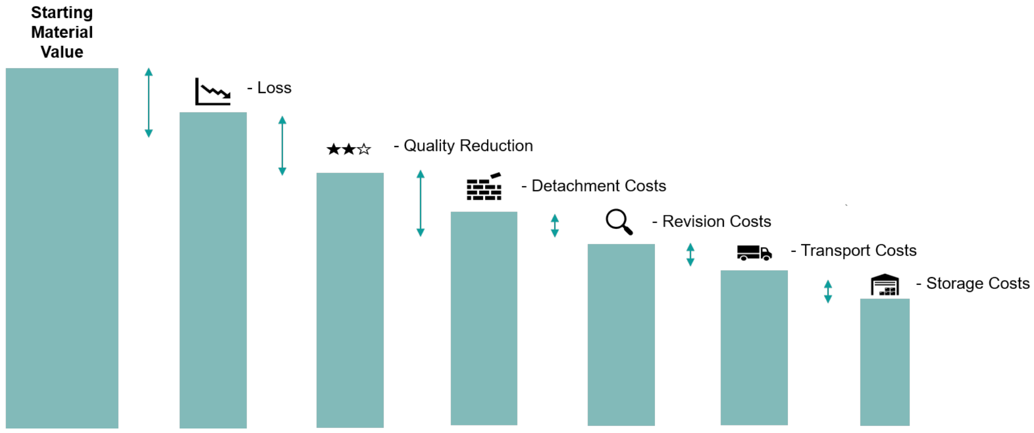

Figure 2.1: Visual representation of calculation theoretical residual reuse value

Table 2.3: Overview of abbreviations and full variable names used in the residual value formula.

Full name	Abbreviation	Explanation
Residual Value	RV	The theoretical financial reuse value of a product after all value-reducing deductions.
Material Value	Vmat	The recoverable material-related share of the direct building cost before deductions.
Loss	L	The share of material value lost due to damage or non-recoverable material fractions.
Quality Reduction	QR	The reduction in value caused by ageing, wear, or technical deterioration of the product.
Detachment Costs	DC	The labour-related costs required to disassemble and detach the product from the building.
Revision Costs	RC	The costs of inspection, repair, and preparation needed to make the product reusable.
Transport Costs	TC	The costs of moving the recovered product from one location to another.
Storage Costs	SC	The temporary storage costs incurred between recovery and reuse.

The chapter further focuses on the primary driving technical parameters and the core residual value formula.

2.2.3. Technical Parameters and Residual Value Formula

Although the formula contains many variables, its behaviour is governed by technical parameters. These are the parameters through which any external intervention must ultimately act, and they therefore define where the policy analysis can engage with residual value:

- The *detachability index (DI)* is the first key variable. It simultaneously governs *loss* and *detachment costs*, and through the write-off threshold it determines whether a product retains any recoverable value at all. This makes detachability a decisive technical determinant of residual value, consistent with the wider circular construction literature on recoverability.
- The *material share* (%material) sets the starting material value base from which all deductions are taken.

- The *labour cost proportion* (%labour) drives the labour costs component of detachment costs.
- The *quality reduction share* (%quality), derived from the product's technical lifespan, governs quality reduction via the NEN 2767 condition-assessment standard.

At its core, the methodology reduces to the relationship in Equation (2.1): recoverable material value less the deductions for loss, quality reduction, and the costs of detachment, revision, transport, and storage. The calculations that form the base of the starting material value and the correction factors can be found in Appendix A.

The formulation also encodes a threshold condition. Where the Detachability Index (DI) falls below 0.25, the product is treated as a write-off and its residual value set to zero, reflecting the principle that a product which cannot be detached without destruction holds no recoverable value.

$$RV = \begin{cases} 0 & \text{if } DI < 0.25 \\ V_{mat} - L - QR - DC - RC - TC - SC & \text{if } DI \geq 0.25 \end{cases} \quad (2.1)$$

The principal technical parameters governing the formula are the material share (%material), the labour share (%labour), the BCI detachability index (DI) — which determines both %loss and $corDI$ — and the technical lifespan, which determines %quality. Together, these four parameters determine both the size of the recoverable material value base and the magnitude of the correction factors deducted from it. They are the points at which policy instruments can, in principle, shift residual value, and accordingly structure the operationalisation developed in Chapter 6. The full set of look-up tables can be found in Appendix A, and a full report of the underlying methodology can be found in the *Circulaire Restwaarde Rekenmethodiek* by (Alba Concepts et al., 2025).

2.3. Structural Materials of Dutch Buildings

2.3.1. Characteristics of a Load-Bearing-Structure

The load-bearing structure typically accounts for a substantial share of a building's total mass and often dominates embodied environmental impacts across the life cycle. Structural design choices therefore materially shape life-cycle externalities, including material resource use, embodied carbon, and end-of-life recovery potential (D'Amico & Pomponi, 2020). Because structural systems are largely responsible for the material intensity of buildings over time, reductions in structural material use can yield disproportionately large environmental benefits (D'Amico & Pomponi, 2020). At the same time, the load-bearing structure is one of the most cost-intensive building layers and represents a substantial share of direct building costs. This combination of high environmental burden and high direct cost makes the structure a particularly relevant focus for residual value analysis: design decisions at the structural level not only determine embodied impacts, but also strongly influence the amount of material value that can potentially be recovered at the end of a building's service life.

Understanding the time horizon of residual reuse value requires attention to the differing lifespans of building elements. The Brand (1995) shearing layers model provides a useful conceptual framework by conceptualising the building as a set of nested layers that change at different rates over time.

Within Brand's framework, the six layers are site, structure, skin, services, space plan, and stuff, each associated with a distinct rhythm of change. *Site* refers to the geographic setting, urban location, and legally defined plot, and is generally treated as having an indefinite lifespan. *Structure* includes the foundation and primary load-bearing elements and typically lasts between 30 and 300 years. *Skin* refers to the exterior envelope and has an expected lifespan of around 50 years. *Services* include installations such as electrical systems, plumbing, sprinklers, communication wiring, and HVAC, with replacement cycles of approximately 7 to 15 years. *Space plan* refers to the interior layout, including walls, ceilings, floors, and doors, and usually changes within 3 to 30 years. Finally, *stuff* consists of movable and user-related items such as furniture, lighting, telephones, and other personal or functional objects, which generally have the shortest lifespan, often less than one year.

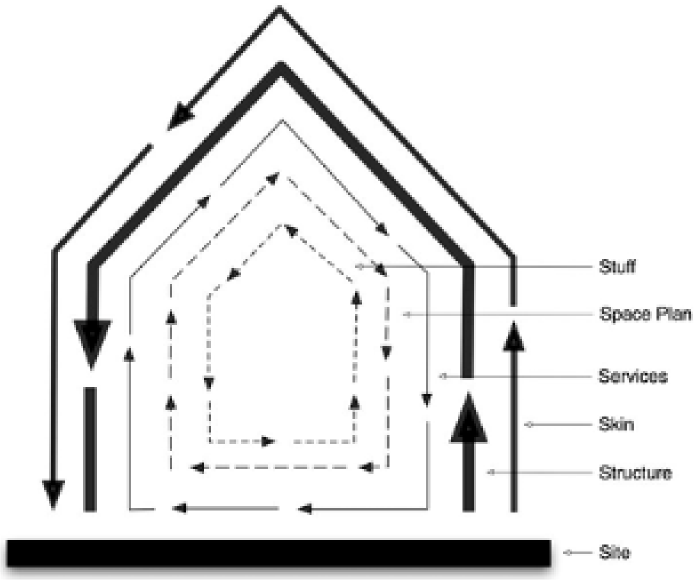

Figure 2.2: Shearing Layer Model, adopted from Brand (1995)

2.3.2. Conventional and bio-based Building Product Materials in the Netherlands

Following the levels-of-scale framework, the analysis now moves from the load-bearing structure to the construction product materials from which that structure is composed. This step is analytically important because residual value is ultimately shaped by material characteristics as well as product design, of the products embedded within it. To assess how financial instruments may affect the residual reuse value of structural systems in Dutch public buildings, it is therefore necessary to understand which materials commonly occur in the Dutch built environment.

In the Netherlands, the most widely used building materials include concrete, brick, and steel. To establish average material intensities per building type, Sprecher et al. (2021) analysed the materials identified in 25 demolition projects in the Netherlands. The dataset was derived from projects handled by a demolition company specialised in reuse and recycling, which provides a useful empirical basis for understanding the dominant material composition of Dutch buildings and for situating the material focus of this thesis.

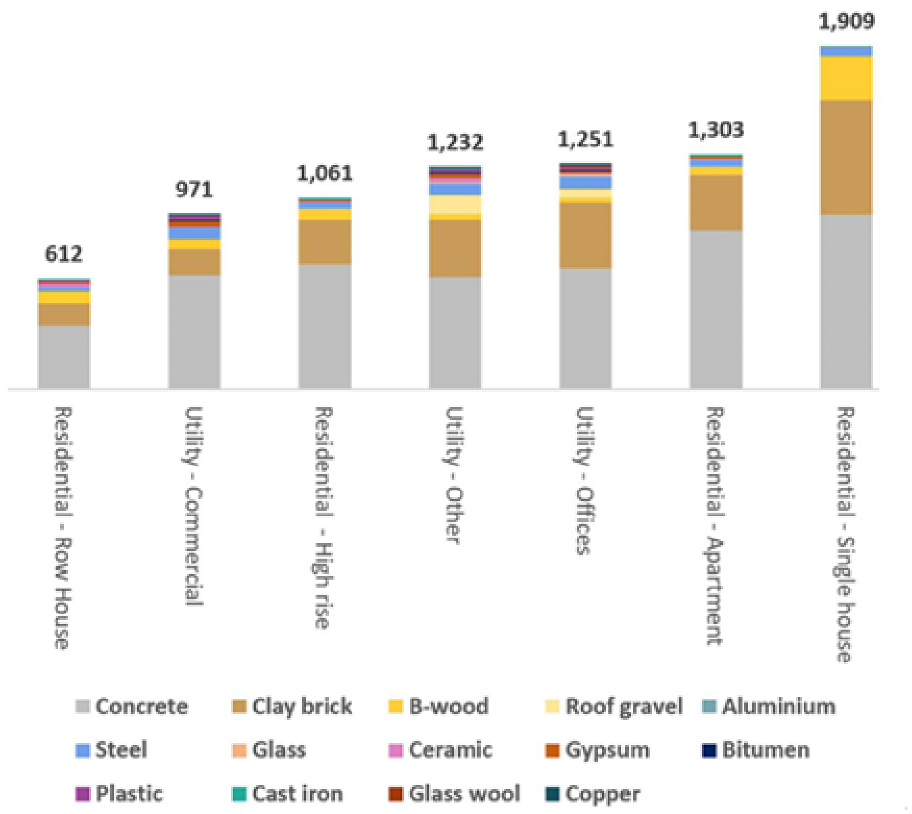

Figure 2.3: Material Usage derived from 25 demolition project in the Netherlands, derived from Sprecher et al. (2021)

In a Dutch context, buildings newer than those researched in this dataset will typically contain more concrete and less brick (Sprecher et al., 2021). Additionally, engineered wood products, such as glue-laminated (glulam) and cross-laminated timber (CLT), have gained increasing popularity due to their environmentally sustainable performance (Duan et al., 2022). Qualities such as the ease and speed of construction due to the high level of prefabrication position mass timber products as a feasible substitute for traditional building materials such as reinforced concrete and steel (Duan et al., 2022). This makes engineered wood products a particularly relevant comparator in this research, as its bio-based character, lower embodied environmental impacts, and prefabricated construction logic are likely to affect key residual value parameters, including labour share, material share, and detachability, in ways that differ systematically from conventional structural materials.

Building further onto this knowledge, this research will specifically focus on three main building materials, being (reinforced) concrete, structural steel and engineered wood products.

2.3.3. Mass quantities of building materials in load-bearing structure

D'Amico and Pomponi (2020) provide one of the most systematic early-stage analyses of structural mass quantities across concrete, steel and wood material typologies. Based on 31,180 parametrically generated frame configurations, they estimate structural mass per square metre of floor area for reinforced concrete, structural steel, and engineered wood in approximate ratios of 5.2 : 3.8 : 1.0 respectively, normalised to timber. These values are compared here with those reported by (De Wolf et al., 2016). Although (D'Amico & Pomponi, 2020) exclude shear walls, cores, foundations, and other substructure components from their system boundary, the normalised ratios remain remarkably similar across both studies.

Table 2.4: Comparative structural mass intensities for concrete, steel, and wood, in absolute (kg/m^2) and wood-normalised values

Source and metric	Concrete	Steel	Wood
D'Amico and Pomponi (2020) [kg/m^2]	465	345	90
De Wolf et al. [kg/m^2]	1090	845	203
D'Amico and Pomponi (2020) [normalised, wood = 1.0]	5.2	3.8	1.0
De Wolf et al. (2016). [normalised, wood = 1.0]	5.3	4.1	1.0

This is analytically important because it suggests that the principal load-bearing elements, beams, columns, and floor slabs, can serve as a credible proxy for broader structural comparison(D'Amico & Pomponi, 2020). For the present thesis, this justifies focusing on beams, columns and floors: together they capture a substantial share of structural mass, direct building cost, and embodied impact, while also constituting the level at which residual reuse value can be meaningfully compared across material systems. The excluded components were left out mainly to keep the scope clear. For foundations, the exclusion also has little effect on the results: they are typically cast in place, score very low on detachability, and therefore fall below the threshold at which the residual value framework treats a product as recoverable. Foundations would count as write-offs with negligible residual value. Walls are excluded for scope clarity.

For the residual value calculations used in this thesis, the importance of this knowledge lies in the fact that once the mass and corresponding construction-product values of the structural elements are known, coefficients such as direct building costs and greenhouse-gas emissions can be estimated by multiplying the relevant coefficient by the mass of each structural material and summing the individual contributions (D'Amico & Pomponi, 2020). This makes mass not only an environmental indicator, but also a practical bridge between structural design and economic valuation.

The next subsections define the load-bearing elements analysed. First, the definitions and structural functions of beams and columns, and floor slabs are given. Then the material typologies: reinforced concrete, structural steel, and engineered wood products.

2.3.4. Building Product and Material Typologies

This section briefly defines the load-bearing element categories and structural material typologies that form the analytical focus of the thesis. Providing these definitions is important because the residual value model and case-study applications do not assess buildings in general, but compare specific combinations of beams, columns, and floor slabs across reinforced concrete, steel, and engineered wood. The overview below therefore clarifies both the functional role of the selected building elements and the main technical characteristics of the material systems through which they are realised.

Table 2.5: Definitions and structural functions of the three load-bearing element categories analysed in this thesis.

Element	Definition	Structural function
Beams	Horizontal structural elements designed to carry loads perpendicular to their length.	Transfer loads from floors and roofs to columns or walls, while resisting bending moments and shear forces.
Columns	Vertical structural elements carrying loads parallel to their length.	Transfer loads from beams, slabs, and upper floors to the foundation, primarily resisting compression and, in some cases, bending moments.
Floor slabs	Flat, horizontal structural surfaces forming floors and ceilings.	Distribute imposed and dead loads across beams and columns and provide structural support for occupancy and use.

3
Methodological Design

This chapter sets out the methodological design of the thesis and justifies the research strategy in relation to the main research question. It specifies the analytical framework, the two-phase research process, case-selection logic, methods, data collection and processing, and the validity considerations and limitations of the approach.

3.1. Research Strategy

The ex-ante policy evaluation research is guided by two frameworks that play distinct roles. The Policy Compass (*Beleidskompas*) of the Dutch government provides the structuring logic: its sequence of questions shapes the research process and the design of the sub-questions, moving the thesis from problem diagnosis to an ex-ante policy evaluation evaluation. The policy-mix analysis of Rogge and Reichardt (2016) provides the evaluative research method: it supplies the analytical procedure for examining how the policy instruments affect an outcome variable and how they perform as a set. In short, the Policy Compass structures *what* is asked and in what order, while the policy-mix analysis structures *how* the resulting instruments are evaluated. The two are integrated within a convergent mixed-methods design, in which quantitative and qualitative data are collected in parallel, analysed separately, and brought together only at the interpretive stage, so that each strand contributes to a fuller understanding of the problem than either could alone (Braun & Clarke, 2006).

This design is appropriate to the problem for three reasons. First, the research question is inherently interdisciplinary, spanning institutional barriers, public policy, circular construction, and financial valuation, and therefore requires methodological triangulation rather than reliance on a single method. Second, the problem is data-limited and future-oriented: because many circular policy mechanisms remain underdeveloped and empirical implementation evidence is scarce, structured expert judgement is a necessary complement to documentary evidence. Third, the ex-ante orientation aligns with the policy ambition of the thesis, which is not merely to describe barriers but to assess whether specific policy instruments could shift the governmental and economic mechanisms that sustain a linear default in Dutch public-sector construction.

The remainder of the chapter is organised as follows. Section 3.2 provides an overview of the methodology. Sections 3.3 and 3.4 describe the two research phases and their methods and data collection and processing. Section 3.5 sets out the case-selection logic, and Section 3.6 consolidates the validity considerations and limitations.

3.1.1. The Policy Compass as a Structuring Device

The policy compass framework is adopted here not as a full social-policy design framework but as a structuring device for a more narrowly defined ex-ante evaluation problem. In its original formulation, the Policy Compass guides policy development through five sequential questions—what is the problem, what is the intended goal, what are the options, what are their impacts, and what is the preferred option, while treating stakeholder involvement as a recurring concern throughout (KCBR, 2024). The five sequential questions guide the research from problem diagnosis and incentive selection in Phase I (Section 3.3) to scenario analysis, sensitivity analysis, and ex-ante evaluation in Phase II (Section 3.4).

Mapping the sub-questions onto this structure ensures that the research moves systematically from problem definition to ex-ante policy evaluation.

The first stage — *what is the problem? what is the intended goal?* — is addressed by SQ1 and SQ2, which identify the barriers, enablers, and mechanisms that sustain the linear lock-in in Dutch structural construction and prevent the recovery of embedded material value. The question — *what are the options?* — is adressed by SQ3 and selects specific instruments most relevant to the identified barriers and mechanisms and residual value methodology variables. The fourth stage — *what are their impacts?* — marks the beginning of phase II, and is addressed by SQ4. *What is the preferred option* is discussed in the closing Chapter 8 'Discussion', where the research findings are interpreted, ultimately answering the main research question related to incentivising circular construction. In this way, the sub-questions reproduce the problem-to-impact progression of the Dutch '*Beleidskompas*', while keeping residual value as the consistent analytical thread linking each stage. The recurring stakeholder question is addressed primarily through structured expert elicitation, complemented by the literature review and policy document analysis.

Two considerations motivate this choice. First, the thesis aims to develop instruments for the Dutch government to incentivise circular construction of public buildings, aligning the analysis with the government's own policy-design framework makes the resulting instruments more likely to be useful to the actors responsible for implementing them. Second, because the framework encodes considerable practical experience in policy design, it reduces the risk that important steps are overlooked when designing a set of instruments.

The present thesis applies this logic in a focused way. Rather than evaluating broad societal policy packages, it applies the five sequential questions to the specific question of how policy instruments affect the residual value of building materials, to incentivise circular construction of Dutch public buildings. This narrower focus is analytically important because the novelty of the research lies precisely in treating residual value as the central evaluative lens through which policy effects are assessed.

3.1.2. Policy Mix Analysis for Evaluation

The policy-mix can be summarised in three steps: the selection of the instruments most suitable among the available options chapter 5; the customisation of those instruments for the context in which they are to operate chapter 6; resulting in the design of an policy instrument mix, that is, a set of distinct and complementary instruments addressing the identified problem (Rosenow et al., 2016) in chapter 7. A policy mix need not be formally recognised, instruments still under development or only partially implemented can be analysed to understand how they do or do not contribute to a given objective (Bessa & Gouveia, 2023). In this thesis, the policy-mix analysis quantifies how the selected instruments affect residual reuse value, and analyses how that contrbutes to circular construction of Dutch public buildings. Policy design features are operationalised from primary sources wherever possible, consistent with the guidance of Rogge and Reichardt (2016). Where design features cannot be read directly from public documents, expert elicitation is used and flagged transparently; structured expert elicitation accordingly serves to validate assumptions, test their plausibility, and identify missing mechanisms or blind spots.

The policy mix is finally evaluated against four characteristics common to policy-mix research frameworks, articulated as guiding questions by Mavrot et al. (2019), and further defined by (Rogge & Reichardt, 2016):

Consistency. Are the elements of the mix aligned toward the same goal?

Coherence. Is the mix synergistic and systemic?

Credibility. Is the mix believable and reliable?

Comprehensiveness. Is the mix extensive and exhaustive?

3.2. Methodology Overview

The research proceeds in two phases: Phase I diagnoses the problem and reviews policy instruments; Phase II selects and operationalises evaluates those instruments through policy-mix analysis. Methods are chosen according to the type of knowledge each sub-question requires: descriptive and conceptual questions are addressed through desk research (literature review and policy document analysis), whereas explanatory and evaluative questions are addressed through a scenario and sensitivity analysis, case study comparison, and expert elicitation. The main research question is stated below, and Table 3.1 maps each sub-question to its method, data collection, and analytical output.

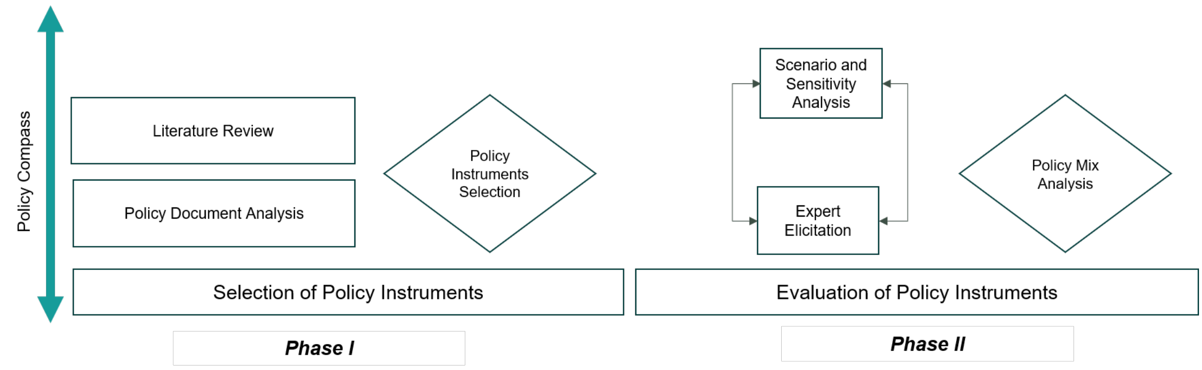

Figure 3.1: Overview of the research design, illustrating the mixed-methods approach.

Main research question. To what extent, and through which mechanisms, do policy instruments affect the residual reuse value of Dutch public buildings, and how can this incentivise circular construction?

Table 3.1: Sub-questions mapped to methods, data, and analytical outputs.

Sub-question	Method	Data collection	Analytical output
SQ1. *What economic and governmental barriers and enablers to circular construction are identified in academic literature?*	Literature review	Academic literature on economic and governmental barriers and enablers	Analytical map of barriers and enablers to circular construction
SQ2. *What economic and governmental mechanisms produce the "linear default" for Dutch public buildings?*	Policy document analysis	Dutch policy documents on fiscal frameworks, procurement, and policy instruments	Analytical insights of institutional mechanisms producing linearity in Dutch construction
SQ3. *Which policy instruments are most suitable for incentivising residual reuse value, given the identified barriers and the variables of theoretical residual value?*	Mixed-method	Literature review, policy documents, and expert elicitation	Selection and justification of candidate policy instruments for policy-mix modelling

Sub-question	Method	Data collection	Analytical output
SQ4. *To what extent do price-based instruments (a labour tax reduction and carbon pricing) and the regulatory instrument (a detachability threshold) affect residual reuse value, individually, relative to one another, and in combination?*	Policy-mix analysis	Residual value calculations, product-level data, embodied-carbon values, case-study inputs, expert-validated assumptions	Scenario and sensitivity model outputs on residual reuse value per case study, policy, and structural configuration

To support transparency, an audit trail of source logs, interview protocols, coding categories, parameter tables, and model assumptions is maintained throughout. This does not eliminate uncertainty, but it makes the analytical pathway visible and reviewable. Prior to the formal research, informal conversations with practitioners during the author's internship at Arcadis served as practice-based scoping input rather than formal elicitation; they informed the decision to analyse differences between materials and to focus on economic value rather than attempting to capture every dimension of circularity in the built environment.

3.3. Methods and Data Phase I

Phase I identifies the barriers to circular construction and the mechanisms that reproduce a linear default in the Netherlands, and on that basis selects candidate policy instruments. It draws on two evidence sources: a literature review and a policy document analysis. Together these guide the Policy-Compass selection of candidate instruments for evaluation in Phase II.

3.3.1. Literature Review

The search strategy combined snowballing with structured database searches across Scopus, Web of Science, Google Scholar, and ScienceDirect, using Boolean combinations of key terms: *circular AND buildings*, *circular AND economy*, *circular AND barriers*, *circular AND enablers*, *stakeholders AND circular buildings*, *policy AND circularity*, and *circularity AND policy instruments*.

The literature review took two works as conceptual anchors: Kirchherr et al. (2018), for its systematic account of barriers to a circular economy, and van Stijn et al. (2023), for its framework linking circular design strategies to the building scale. These defined the core vocabulary and principal lines of debate, from which the review was extended through backward and forward snowballing.

3.3.2. Policy Document Analysis

The Policy Document Analysis examined grey literature on circularity in Dutch construction, including policy-focused documents commissioned by the national government. Policy document analysis is commonly used as a supplementary means of data collection that adds rigour through multi-method triangulation. Table 3.2 summarises the selected documents and their relevance to the research.

Table 3.2: Policy document selection and relevance to the research.

Translated title (Dutch to English)	Author	Public governing structure	Relevance to the policy document analysis (PDA)
Financial Incentives for a Circular Economy	(KPMG, 2025)	Commissioned by the Ministry of Infrastructure and Water Management	Used to identify promising fiscal and economic instruments for accelerating the circular economy in the Dutch context, including in the construction sector

Translated title	Author	Public governing structure	Relevance to the PDA
Impact Assessment of Circular Construction Economy Priorities	(USP, 2024)	Rijksdienst voor Ondernemend Nederland (RVO)	Used to identify the main implementation priorities and policy themes in the Dutch circular construction economy across stakeholders
Analysing instruments towards a Sustainable Secondary Material Supply Chain	(van Raak et al., 2024)	Commissioned by the Ministry of Infrastructure and Water Management	Provides an empirically grounded overview of the main implementation bottlenecks, stakeholder priorities, and policy themes in the Dutch circular construction economy

3.4. Methods and Data Phase II

Phase II evaluates the selected instruments through the policy-mix analysis defined in Section 3.1.2, drawing on structured expert elicitation, product-level material data, and case-study inputs. This section describes the collection and processing of each.

3.4.1. Structured Expert Elicitation

Purpose and data. The expert elicitation synthesises two forms of evidence: quantitative estimates, in which candidate parameter values were presented to experts to capture both consensus and the range of judgements around each parameter; and qualitative insights, assumptions, and causal models, which were summarised and carried through the research and model development. Together these validate assumptions, test scenario plausibility, and provide the model validation.

Interview procedure Prior to each interview, participants received an information and informed-consent form outlining the purpose of the study, the intended use of the data, the voluntary nature of participation, and the conditions for confidentiality and data processing. The interview protocol was pilot-tested with quasi-experts (advanced graduate students in Architecture and Building Technology) to ensure that the questions and the model visualisations were workable and comprehensible (Morgan, 2014). Ten semi-structured interviews were then conducted, predominantly individually to reduce conformity effects (Meyer & Booker, 1990). Where consent was granted, interviews were audio-recorded; otherwise detailed written notes were taken. A visual presentation of the scenario model, its core parameters, and the policy mechanisms under consideration was used throughout to ground expert judgements in a shared interpretation of the model logic.

Expert selection The ten experts were purposively selected for their relevance to the research question, with the aim of covering the main knowledge domains required (Lee, 2025). Their expertise spanned theoretical residual value, circular construction, construction costs, circular policy design, concrete and steel reuse, circular financing, and public building commissioning. Selection further required demonstrated professional experience with material reuse, valuation, public-sector construction, or circular project implementation. The objective was analytical breadth and diversity of judgement rather than statistical representativeness.

Coding and processing Interviews were transcribed or converted into structured notes, anonymised, and coded according to predefined analytical functions, distinguishing expert input used for model building from input used to qualify or limit interpretation. The coding structure is summarised in Table 3.3. A summary of the interviews is provided in the Appendix.

Table 3.3: Expert elicitation interview coding structure.

Expert elicitation function	Interview focus	What is being coded	Analytical purpose in the thesis
Calibration seeds	Professional experience with circular construction, reuse projects, residual value applications, and cost or valuation practice	Type and depth of expertise; direct experience with reuse value, reuse of building materials, public real estate, public-policy construction engineering, or circular real estate	To assess whether the expert is sufficiently qualified to judge model assumptions and scenario logic, and to contextualise variation in responses
Scenario plausibility	Plausibility of carbon pricing, labour tax shifts, and baseline versus transition scenarios in the Dutch context	Judgements on realism, feasibility, expected timeframe, and institutional plausibility of each scenario	To test whether the selected scenarios are analytically credible rather than merely theoretically attractive
Transmission logic	How carbon pricing and labour tax changes are expected to affect residual value and circular-construction choices	Statements on causal pathways, market responses, procurement effects, and likely changes in labour or material cost structures	To validate the causal logic linking policy instruments to residual value outcomes in the scenario model
Assumption validation: base-model values	Direct building costs, correction factors, structural materials, embodied carbon	Support, uncertainty, disagreement, or suggested range adjustments for each parameter and correction factor	To refine the parameter baselines and ranges used in the model and sensitivity analysis
Assumption validation: technical parameters	Direct building costs, detachability, %labour/%material, %quality	Support, uncertainty, disagreement, or suggested range adjustments for each parameter and correction factor	To refine parameter assumptions, identify sensitive variables, and justify the parameter ranges used in the model
Assumption validation: model inputs	Residual value formula parameters and correction factors such as revision, storage, and transport costs	Material-specific confirmations, concerns, boundary conditions, and differences between product categories or structural systems	To check whether the model treats material groups and correction factors consistently with sector practice

Function	Interview focus	What is being coded	Analytical purpose
Model Validation: completeness check	Open questions on missing mechanisms, overlooked barriers, or blind spots	Mentions of additional institutional, governmental, economic, or other barriers; policy interactions; missing factors; implementation risks	To assess whether the model captures the most relevant mechanisms and to identify where conclusions should remain cautious

3.4.2. Building-Product Material Data

Data Collection The quantitative evidence base comprises product-level residual value data, direct building costs, labour and material shares, detachability indices, quality assumptions, embodied-carbon values, and case-specific structural quantities, drawn from the Revalto methodology, Arcadis/BDB-related datasets, literature on structural material mass, and documented building cases. Where direct observations are unavailable, assumptions are made explicit and subsequently tested through expert elicitation and sensitivity analysis.

Two dataset-specific points warrant note. First, the quality-reduction correction factor (%quality) is derived from the assumed service life: under the lifespan assumptions applied here, structural steel and reinforced concrete correspond to a %quality value of 30%, whereas engineered wood corresponds to 0%, indicating no meaningful quality-related deduction within the model horizon. Second, the %labour and %material shares in the dataset do not always sum to 100%, because the underlying data distinguish the subcontracted-labour share from the broader labour-plus-equipment share; the subcontracted-labour component falls outside the scope of this research and is excluded from the calculation of labour costs, including the detachment-cost component of the residual value model.

Data Processing Quantitative data were cleaned and standardised before modelling: harmonised across units of measurement where necessary, checked for internal consistency between labour share, material share, and total direct building cost, and linked to the correct structural-element category. Where values came from different sources, preference was given to Dutch or case-relevant data, with any substitutions or extrapolations documented. Sensitive project data were anonymised or normalised, for example by expressing costs per square metre or removing identifiable project details where confidentiality required.

3.4.3. Case-Study Model Data

Data Collection A purposive approach was used to select a minimum of two projects, prioritising comprehensive material and cost breakdowns; a comparison between conventional materials (reinforced concrete and structural steel) and either a bio-based alternative (engineered wood) or a design-for-disassembly approach (a detachable reinforced-concrete floor); and documentation sufficient to align with the available dataset.

Data Processing Building products were extracted from the Revalto dataset and defined on the basis of the NL-SfB classification, each product representing a combination of NL-SfB “structure” classifications combined with floor slabs, and structural systems (columns and beams). Products were sorted by material typology (reinforced concrete, structural steel, and engineered wood—HSB, glulam, CLT) and by construction method (prefabricated or in-situ). For each product, the following parameters were obtained: unit price (€/kg, €/m, €/m^2); labour share $\%lab_0$ (labour share equipment); material share $\%mat_0$; detachability index (DI); %quality; and weight (kg).

Where the mass of structural materials is known, coefficients such as direct building cost and emissions are estimated by multiplying material quantities by the relevant factor and summing the contributions

(D'Amico & Pomponi, 2020). The initial building cost is defined as:

$$DB_{input} = \text{Unit price} \cdot (\text{kg / m / m}^2).$$

3.4.4. Scenario and Sensitivity Analysis

All calculations were conducted in Microsoft Excel. The full workbook, including input data, parameter values, and underlying calculations, is available via the TU Delft repository.

Data collection for the building-product material inputs is described in Section \ref{data-collection-building-product-materials}. The Excel model complements this document, with key tables provided in Appendix D.

A deterministic one-at-a-time (OAT) sensitivity analysis was performed in Excel and visualised as a tornado diagram. This analysis assesses the extent to which individual parameters influence model outcomes. Each parameter is varied across a defined plausible range while all others are held constant at their baseline values, allowing the isolated effect on residual value to be identified. The tested parameter ranges are not uniform across parameters: —±20% for continuous variables, discrete band changes for lookup-based correction factors, and a one-sided stress test for revision costs. The parameter rankings reflect sensitivity within each parameter's plausible range rather than a normalised elasticity. They should be read as indicative of which assumptions matter most under realistic variation, not as standardised sensitivity coefficients.

The parameters considered are grouped into three categories: policy-related parameters, technical correction factors, and general cost assumptions. Parameter ranges are informed by the expert elicitation and the author's analysis. The resulting tornado diagram ranks parameters according to their influence on model outcomes, thereby identifying those variables to which the residual value estimates are most sensitive.

3.5. Case-Study Selection Logic

Case selection follows a purposive, theory-informed logic rather than a statistical sampling logic. The aim is not a representative sample of Dutch public buildings, but cases that allow the residual value model and the policy scenarios to be applied in a substantively meaningful and analytically transparent way. Three criteria guided selection:

1. Cases had to contain sufficiently detailed information on structural materials, quantities, and direct building costs to enable translation into the residual value model.
2. Cases had to be policy-relevant within the BBV accounting framework for municipal real estate, which is why public buildings, and school buildings in particular, were prioritised.
3. Cases had to support comparison between conventional and more circular or bio-based alternatives, whether through realised comparative projects or well-documented paired design variants. This comparative logic is essential because the thesis does not assess a single building in isolation, but examines how policy instruments alter the *relative* financial attractiveness of different material choices.

Because the application of residual value to public buildings remains highly novel, identifying suitable comparative cases proved challenging. Through stakeholder interaction over the course of the thesis, and systematic exploration of external data sources, two cases meeting these requirements were ultimately identified, and their suitability and underlying assumptions were further substantiated through expert validation. Given the scarcity of empirically comparable examples in both practice and research, this is itself a meaningful outcome.

Because the research partly relies on external sources to estimate structural mass values, it is exposed to the methodological challenges associated with data of uncertain quality, relevance, or comparability—a difficulty especially salient in construction research, where data are often fragmented and insufficiently detailed for direct analytical use (D'Amico & Pomponi, 2020). To mitigate this, averages are avoided in favour of matching specific building products to the Revalto dataset, and all assumptions were validated in the expert elicitation. The resulting strategy, which combines project-specific data with standardised Dutch building-product data and validated assumptions, is a pragmatic but defensible compromise: it increases feasibility and allows the model to be applied under realistic Dutch conditions, but it limits the strength of generalisation claims. The methodological value of the cases lies in demonstrating how the scenario model performs under grounded and policy-relevant conditions. After selection of the case studies, the units of analysis are illustrated in figure 3.2.

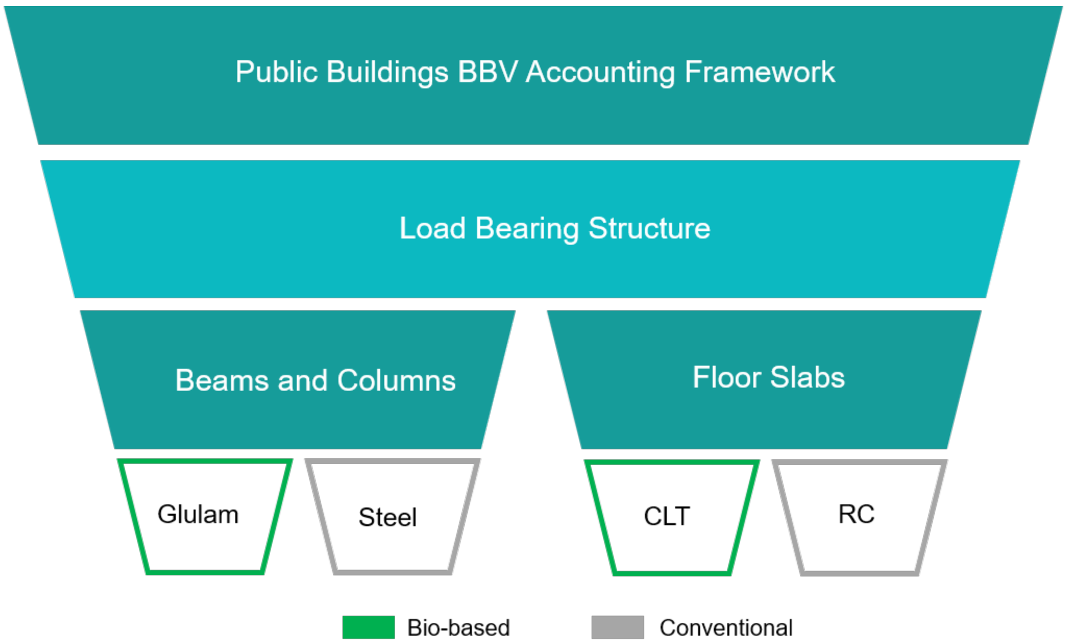

Figure 3.2: Visual representation of the units of analysis

3.6. Validity and Limitations

Given the prospective, model-based character of the study, methodological quality depends less on statistical representativeness than on conceptual validity, triangulation, and transparency.

Validity Validity is strengthened by making the causal logic explicit: policy instruments are translated into changes in clearly specified model parameters, and the relation between those parameters and residual value is validated through expert elicitation. Internal validity is reinforced through the combined use of literature review and policy analysis, scenario and sensitivity analysis, and expert elicitation, which aims to reduce the risk that conclusions rest on a single source of evidence. Interpretive validity is supported by integrating qualitative and quantitative findings at the stage of analytical interpretation.

Reliability Reliability is supported through systematic documentation of assumptions, case-selection decisions, parameter values, elicitation prompts, and coding logic. It nonetheless remains bounded: different experts might offer different judgements, alternative case-study assumptions could shift model outputs, and the simplification required for scenario and sensitivity analysis necessarily omits part of the real-world complexity of implementation. These are not incidental weaknesses but structural features of ex-ante policy analysis.

Reliability, bias, and uncertainty across sources Data reliability varies across sources. Model data are precise only within the assumptions that structure them, and expert elicitation provides informed judgment rather than direct observation. Bias may enter through selective case availability, researcher choices in parameterisation, and the professional backgrounds of the experts; it is minimised through triangulation, documentation, pilot testing, and the deliberate inclusion of experts from different domains. Uncertainty is both empirical, arising from incomplete data, uncertain parameter values, and imperfect case comparability, and structural, arising because the model necessarily simplifies market dynamics, political feasibility, behavioural responses, and wider implementation pathways. The thesis addresses these uncertainties not by claiming to eliminate them, but by making them explicit, testing the sensitivity of results to them, and incorporating them into the interpretation of findings. A further constraint concerns the policy-mix concept itself: Rogge and Reichardt (2016) caution changes in other policy fields such as market regulations or tax rules, large uncertainty about future developments (technical, political, cultural); and the desired direction of change and the complexity of the change process is significant.

Scope limitations. Four limitations follow from the design and should be stated explicitly. First, the thesis examines a bounded set of policy instruments and a limited number of structural material groups, which improves analytical clarity but narrows scope. Second, the model prioritises variables that can be operationalised with relative clarity, labour cost, material share, detachability, and embodied-carbon exposure, while broader market dynamics, stakeholder adaptation, legal implementation pathways, and political feasibility are partially captured. Third, residual reuse value is only one dimension of circularity and should not be mistaken for the full social or environmental value of circular construction. Fourth, because the study uses selected Dutch cases and policy relevant building, the findings are most credible for Dutch public real estate and comparable (international) contexts rather than universally generalisable.

An iterative procedure Finally, the procedure described above is applied as a learning process rather than a fixed sequence. Boundaries set initially may change as the work proceeds, with each step able to revise those preceding it. Part of this thesis's methodological contribution therefore consists in developing or refining indicators that link policy instrument design features to residual value through expert elicitation. The methodological contribution of the thesis thus lies not in prediction, but in providing a transparent and analytically defensible way of reasoning about policy effects on circular value retention under uncertainty.

4

Identification of Circular Construction Barriers, Enablers and Mechanisms

This chapter develops the foundation for selecting the policy instruments examined in the thesis. It proceeds in two steps. Section 4.1 identifies the main economic and governmental barriers and enabling conditions discussed in the academic literature on circular construction. Section 4.2 then examines how these barriers are reproduced in the Dutch context as a linear default through a comparative analysis of three policy documents. This chapters formulates an answers to the sub questions *'What economic and governmental barriers and enablers to circular construction are identified in academic literature?' and* 'What economic and governmental mechanisms produce the 'linear default' for Dutch public buildings?'

4.1. Literature Review: Governmental and Economic Barriers and Enablers for Circular Construction in the Netherlands

The intended goal of the literature review is to identify which financial incentives are suitable to increase the residual value to incentivise circular construction. *'What economic and governmental barriers and enablers to circular construction are identified in academic literature?'* This section reviews the academic literature on economic and governmental barriers and enablers to circular construction.

4.1.1. Stakeholders, Scale and Structure of Academic Landscape

Peng and Cao (2025) categorises the key stakeholders in circular construction into seven categories. Policymakers, the construction and engineering sector, raw material and product related sector, end-user, transport operator, academic advisors, and the recycling, demolition, and disposal sector as a new stakeholder in the circular project life cycle, which is defined by terms such as recycling companies, waste management companies, and landfill owners in previous research.

Existing studies have mapped barriers comprehensively, but drivers, enablers, and opportunities to a far lesser extent. A literature review by van Stijn et al. (2023) provides one of the most complete mappings of barriers to circular construction to date, identifying 55 economic and financial barriers and 37 governmental and regulatory barriers across the surveyed studies, together the two most numerous categories, followed closely by educational barriers. This numerical prevalence offers empirical justification for concentrating on the economic and governmental barriers and enablers.

A second justification is theoretical. Kirchherr et al. (2018) show that barrier categories are not isolated but interrelated. In their account, economic and market conditions, most notably low virgin-material prices, sit near the root of the chain: they allow linear products to outcompete circular ones, which suppresses consumer interest and awareness, which in turn sustains a hesitant company culture and continued operation within a linear system. Apparent technical and financial obstacles, such as high upfront investment costs, may therefore be symptoms of this dynamic rather than independent constraints. This ordering has a direct implication for instrument selection: acting on economic conditions is intended to reach the behavioural and technological dimensions indirectly, because economic conditions shape whether circular choices become viable at the level of procurement and design. The focus of this thesis on economic and governmental barriers is thus justified both empirically, by their prevalence in the literature, and theoretically, by the causal position they occupy.

4.1.2. Governmental Barriers and Enablers associated with Circular Construction and Buildings

Allam and Nik-Bakht (2023), in a synthesis of nine empirical studies, identify four political barriers as particularly prominent in the construction sector: insufficient governmental financial support for circularity strategies, contradictions between regulations, legislative uncertainty and regulatory instability, and the absence of circularity-specific guidelines. Together, these barriers create a policy environment in which circular practices remain difficult to implement, not because of technical infeasibility alone, but because the institutional conditions required for long-term investment, compliance certainty, and operational standardisation are weakly developed. Munaro and Tavares (2023), in a review of 47 articles on circular economy implementation in construction, reinforce this diagnosis and further identify the absence of public financial aid and fiscal action as a structural political gap. Their findings suggest that when effective governance is implemented collaboratively across the construction value chain, political intervention can trigger a broader cascade effect across both barriers and drivers, thereby functioning as a primary lever for systemic change. In a similar vein, Cruz Cruz Rios et al. (2021) argue that regulatory and financial barriers should not be treated as fixed structural conditions, but rather as institutional design choices that can be reconfigured into enabling conditions. This reframing is foundational to the thesis. Approaching policy instruments not merely as corrective responses to isolated market failures, but as instruments through which the institutional logic that produces a linear default can be actively reconfigured, reflects the logic that Cruz-Rios and Grau (2020) articulate: barriers become drivers when the policy design changes.

4.1.3. Economic Barriers and Enablers associated with Circular Construction and Buildings

The previous mentioned literature review in March 2022 by van Stijn et al. (2023) found governmental and economic barriers to be the most mentioned. These barrier could be summarized as the ‘additional time, labour and costs to design and construct when applying circular design options.’ Calisto Calisto Friant et al. (2021) articulates this most sharply: if price signals favour linear models, circular options will remain niche sectors of the economy. As the iron triangle of time, scope, and budget governs decision-making in construction (Kooter et al., 2021), making financial competitiveness is a prerequisite for adoption. Specifically for circular materials, Munaro and Tavares (2023) and Mhatre et al. (2020) identify the higher production and operating costs of secondary material flows as a primary obstacle, discouraging stakeholders from adopting circular practices even if sustainability ambitions are present.

Azcarate-Aguerre et al. (2022) add to this by stating the current regulatory efforts to accelerate circularity in the building stock fail to overcome three reinforcing economic barriers, where high initial investment costs, misaligned policy instruments among stakeholders, and the persistently low cost of unsustainable building materials. However, research by AlJaber et al. (2023), state that circular implementation is often perceived as costly not only because of actual cost differentials, but also because of insufficient regulatory frameworks and limited awareness of lifecycle benefits. This perception is itself a barrier, as it influences procurement behaviour and investment strategy even if cost difference is not identified as its main barrier. Finally, Tirado et al. (2022) identify the absence of incentives for end-of-life design as a fundamental structural gap. Without a regulatory requirement or financial reward for design for disassembly, there is no procurement-level signal to integrate recoverability into the initial design and construction process.

These economic barriers interact in ways that are particularly relevant for this thesis. High upfront circular costs are as of now rarely compensated by circular depreciation through residual value, because prevailing valuation conventions render that value largely invisible, while the artificially low price of virgin materials suppresses the market signal that would otherwise favour circular alternatives. These mechanisms are causally interconnected rather than independent. High upfront circular costs are rarely compensated by circular depreciation through residual value, because prevailing valuation conventions render that value largely invisible, while the artificially low price of virgin materials suppresses the market signal that would otherwise favour circular alternatives. Breaking this cycle requires interventions at more than one point simultaneously.

Critically, literature confirms that these mechanisms are not isolated but causally interconnected. Or as Kirchherr et al. (2018) states, informational and institutional barriers collectively determine political barriers, which determine economic barriers, which in turn determine technological barriers. In addition to economic and governmental barriers, the literature review identifies barriers and enablers rooted in other domains such as the behaviour, stakeholder alignment, knowledge, and culture of construction sector actors. While social barriers are not directly targeted by policy instruments examined in this thesis, their existence sets a practical limit on how quickly price signals alone can transform the sector. At the same time, these behavioural constraints do not arise in isolation but interact with broader economic and governmental conditions.

4.2. Policy Analysis: Governmental and Economic mechanisms producing the linear default in a Dutch Context

To answer the second research question, *'What economic and governmental mechanisms produce the 'linear default' for Dutch public buildings?'*, this section analyses three Dutch policy documents that together map the institutional mechanisms producing the linear default for public building commissioners in the Netherlands. The three documents were selected for their complementarity, where each occupies a different institutional standpoint and contributes a different layer of diagnosis. KPMG (*Knelpunten en Prikkels Circulaire Bouweconomie*) offers a normative, consultancy-driven assessment of structural barriers and candidate fiscal instruments, valuable for its directional framing but limited by the absence of quantitative substantiation. RVO in collabortation with USP (2024) provides the most empirically grounded perspective, drawing on 338 structured interviews across the full construction chain, though its survey methodology precludes causal inference. Tauw/Drift (*Prikkels en Interventieopties Secundaire Bouwstoffen*) delivers the most analytically rigorous treatment of secondary material chain economics, at the cost of a deliberately narrow scope that excludes the design and procurement dimensions of the circular transition.

KPMG in *Knelpunten en Prikkels Circulaire Bouweconomie* (KPMG, 2025), identifies circular construction as structurally more expensive and more risky than linear construction, primarily because primary construction materials remain cheaper than secondary alternatives, while circular building requires more labour, more time, and more process steps for recovery, sorting, and application. The report further notes that circular construction is perceived as riskier because the supply of secondary materials is less certain and more dependent on demolition and harvesting practices, while certification trajectories for reused or alternative materials remain time-consuming and institutionally demanding. At present, the sector consumes far more material than is released through demolition, which further constrains the availability of reusable inputs. Against this background, KPMG evaluates several candidate fiscal instruments. It concludes that VAT reduction on reused materials is legally constrained and likely to have only a limited price effect because labour remains a large share of total circular construction cost. More promising are routes identified were a higher pricing of virgin raw materials, and the removal of regulatory barriers, for example in relation to the classification and outflow of harvested materials. In addition to policy instruments, the report therefore points to the importance of incorporating circular norms and requirements into building standards.

Tauw/Drift in *Prikkels en Interventieopties Secundaire Bouwstoffen* (van Raak et al., 2024), delivers the most analytically rigorous treatment of secondary material chain economics, however, deliberately narrows the scope that excludes the design and procurement dimensions of the circular transition excluding highly topical developments such as rising primary raw-material costs, increasing energy and CO_2 (ETS) costs, and shifting consumer preferences. Tauw/Drift analyses the economic logic of secondary material chains, finding that market prices are structurally distorted: negative at the start of secondary chains (disposal cost), positive at the point of application, but insufficient to cover the full costs of labour such as transport and processing, with recycling granulate as the sole self-sustaining exception. Crucially, the report also identifies perverse incentive structures within existing instruments. For example, the MKI methodology discourages further material purification. The document is the most analytically rigorous of the three but explicitly limits its scope to secondary material streams, leaving the broader design and procurement chain of building materials unaddressed.

The report by RVO/USP *Effectmeting Circulaire Bouweconomie* (USP, 2024), provides the most empirically grounded perspective, drawing on 338 structured interviews across the full construction chain. The findings suggest the main barrier identified in literature is validated by Dutch stakeholders, which is that circular construction is perceived as too expensive, while restrictive legislation, insufficient knowledge and awareness, the absence of a uniform assessment framework, and weak market demand and supply are also seen as major barriers. Overall, the document confirms that cost, institutional misalignment, and knowledge deficits continue to structure the linear default in practice, while also showing that organisational capability and market positioning are seen as important but underutilised opportunities.

All three documents converge on the diagnosis that circular construction is structurally more expensive than linear construction, but they differ substantially in analytical depth. KPMG attributes this to low raw material costs and additional labour hours. RVO confirms the perception empirically: cost barriers are the most frequently cited structural obstacle across all stakeholder groups. Tauw/Drift provides the most precise diagnosis, distinguishing stating secondary materials start with a negative value, and additionally identify cost factors such as processing and transport costs as a critical variables.

Two features of the current Dutch landscape provide an example for this, where policy instruments adress linear harm without rewarding circular value. The first emerges from the Tauw/Drift analysis, which identifies perverse incentives embedded within existing instruments: the MKI (Milieukostenindicator) methodology can, in certain configurations, discourage further purification of recovered materials, so that the metric meant to steer toward environmental quality actively penalises a higher-value circular outcome. The instrument thus not only fails to reward recovery, but in places works against it.

The MilieuPrestatie Gebouwen (MPG) requirement functions as a regulatory ceiling on the environmental impact of new buildings, framing sustainability as a maximum allowable burden rather than an objective to be minimised. MPG stands for the Environmental Performance of Buildings, referring to the environmental impact of the materials used in construction. It is based on a life cycle assessment (LCA) and calculates the environmental burden of building materials per square metre of usable floor area per year. Compliance is achieved once a building remains below a defined limit at the design stage, aiming to constrain environmentally harming outcomes. The 2026 revision Rijksdienst voor Ondernemend Nederland (RVO) (2026) broadens its scope, tightening requirements for offices (1.55), setting 1.6 for residential buildings, and extending applicability to schools, healthcare facilities, retail, and other publicly procured buildings. However, the underlying incentive structure remains unchanged. The MPG penalises environmental impact only when the threshold is exceeded, while implicitly allowing impact up to that level without differentiation. As a result, buildings that comply are treated equivalently to those that substantially reduce environmental impact or retain residual material value, offering no reward for outperforming the MPG threshold. This suggests environmental impact is treated as an allowable budget up to the threshold, rendering a certain level of impact permissible rather than incentivising lowering environmental impact.

4.3. Synthesis Barriers and Mechanisms Analysis

The findings suggest policies are disconnected from integrating financial decision-making logic at design, procurement, valuation, and end of life. The mechanism through which the linear economy default is reproduced is that value that is created through circular choices, often remains too invisible and therefore reproduce economic barriers to circular construction. Sections 4.1 and 4.2 therefore do more than confirm that circular construction remains disadvantaged; they identify the specific mechanisms through which that disadvantage is reproduced. On this basis, the six synthesised barriers and enabling insights summarised in Table 4.1 provide the immediate foundation for the instrument selection developed in the following chapter (Chapter 5).

Taken together, Sections 4.1 and Section 4.2 do more than confirm that circular construction remains disadvantaged; they also narrow the field of intervention by identifying the specific mechanisms through which this disadvantage is reproduced.On that basis, six synthesised barriers and enabling insights in provide the immediate foundation for the selection made in the following chapter, where policy instruments are selected for policy mix analysis.

Table 4.1: Synthesis of six economic and governmental barriers and enabling insights identified across the academic literature review and the Dutch policy-document analysis

Category	Barrier identified	Academic literature basis	Dutch policy-document alignment
Economic	Virgin materials remain structurally too cheap	Environmental externalities of primary production are not priced at procurement, keeping secondary and bio-based materials at a structural cost disadvantage (Azcarate-Aguerre et al., 2022; Mhatre et al., 2020; Munaro & Tavares, 2023).	Confirmed by KPMG and Tauw/Drift: primary materials remain cheaper than secondary alternatives, and current price structures favour linear procurement.
Economic	Labour-intensive circular activities remain too expensive	Disassembly, inspection, repair, and remanufacturing impose a disproportionate cost burden relative to linear demolition, and are repeatedly identified as a central barrier (Kooter et al., 2021; van Stijn et al., 2023).	Confirmed by KPMG, RVO/USP, and Tauw/Drift, all of which identify labour, processing time, and recovery effort as major cost drivers.
Economic	Residual value remains invisible in prevailing valuation frameworks	Future material value is rarely reflected in procurement, valuation, or accounting decisions, so higher upfront circular costs are not compensated by end-of-life value (AlJaber et al., 2023; Azcarate-Aguerre et al., 2022).	Reflected indirectly through weak financial recognition of circular value and the limited integration of residual value into mainstream decision-making.
Governmental	No binding requirement or strong incentive for Design for Disassembly	Without a regulatory requirement, there is no procurement-stage signal to integrate recoverability, leaving end-of-life design largely voluntary (Allam & Nik-Bakht, 2023; Tirado et al., 2022).	Aligned with KPMG and RVO/USP: circular requirements remain weakly embedded in standards, procurement routines, and regulation.
Governmental	Fiscal distortions and absent public support reinforce linearity	The absence of public financial aid and fiscal action means circular practices must compete within a system designed for linear production (Allam & Nik-Bakht, 2023; Munaro & Tavares, 2023).	Strongly reflected in KPMG and Tauw/Drift: missing fiscal support, weak incentives for harvesting and reuse, and institutional barriers around certification and material outflow.
Governmental	Barriers are institutional design choices and therefore redesignable	Governmental and economic barriers are not fixed constraints but institutional design choices that can be transformed into enabling conditions through targeted policy support (Cruz Rios et al., 2021; Munaro & Tavares, 2023).	Consistent with the Dutch analysis: the problem is not the absence of instruments, but their weak connection to procurement, design, valuation, and stakeholders decision logics.

5 Selection of Policy Instruments

This chapter answers the third sub-question: *Which policy instruments are most suitable for incentivising residual reuse value, given the identified barriers and the variables of theoretical residual value?*

The selection logic is twofold. Each candidate incentive had to respond to one or more the dominant barriers and enabling conditions identified through the literature review and Dutch policy document analysis in Chapter 4; and each had to correspond to a variable so that the instrument could be operationalised within the theoretical residual value methodology introduced in Section 3.1.2 and Appendix A. The selection therefore does not reflect policy relevance in general terms, but policy relevance in relation to the specific analytical model used in this thesis. Rather than reviewing all policy instruments, the chapter narrows to policy instruments that can be expressed as a change in the residual value formula.

5.1. Policy Instruments Typology for Ex-Ante Evaluation

Public policy is a set of theoretical and practical instruments developed to address societal problems across different temporal and geographical contexts (Ruiz Estrada, 2011), and may take the form of regulatory standards, taxation, subsidies, public investment, infrastructure provision, knowledge and skills development, procurement, or stakeholder engagement (Gobbo et al., 2021). For an ex-ante evaluation, this breadth has to be narrowed to a focused policy instrument typology.

Rana et al. (2021) distinguish two policy instrument groups which function as financial incentives: command-and-control (CAC) instruments, which operate by setting binding requirements, thresholds, or limits; and market-based instruments (MBIs), which influence behaviour through market signals. They further subdivide MBIs into market-friction-reduction, rights-based, and price-based instruments such as taxes and subsidies. This distinction is not merely descriptive. It determines how an instrument enters the residual value model: a price-based MBI acts on the cost terms of the formula, whereas a CAC instrument acts on a design parameter. The typology therefore provides the conceptual basis for positioning, and ultimately selecting, the instruments analysed in this thesis.

5.2. From Diagnosis to Policy Instrument Selection

Milios (2017) identifies three policy areas as particularly relevant for circular construction: reuse, repair, and remanufacturing; green public procurement and procurement for innovation; and policies that strengthen secondary-material markets. These areas act at different stages of a building product's life — production, design, procurement / consumption, and end of life — and together they explain how policy can redirect materials away from linear end-of-life pathways. As Milios (2017) argues, outcomes are the product of interactions between multiple policies across a product's life cycle, where instruments may reinforce, constrain, or complement one another.

Figure 5.1 sets out final selection logic in three steps. The barriers identified in 4.1 are synthesised into three critical points. A suitable policy instrument is chosen for each barrier. Each incentive is finally mapped onto a policy-sensitive variable within the residual value methodology. This is the move that allows a qualitative diagnosis of the linear default to become a quantitative representation of how policy instruments may alter residual reuse value and how this can contribute to circular construction.

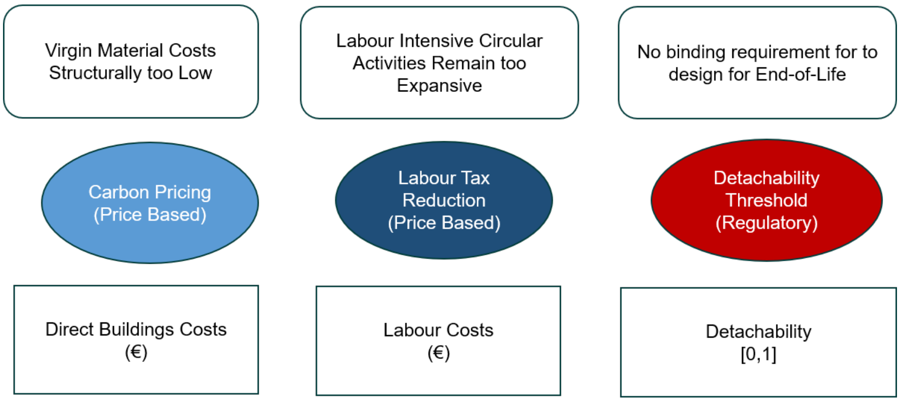

Figure 5.1: Visual representation of selection logic of policy instruments

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Table 5.1 synthesises how each selected instrument enters the residual value methodology, linking the instrument to the mechanism through which it does so, and its expected effect on residual value. This makes explicit the twofold selection logic in operational terms: each instrument is tied to a concrete variable in the formula.

Table 5.1: Synthesis of how the selected policy instruments affect the residual value model parameters and the expected direction of their effect on residual value.

Policy instrument	Parameter affected (unit)	Mechanism	Expected effect on residual value
Labour tax reduction (price-based)	Share of labour; share of material (%)	When the labour tax rate falls, the labour share of direct building cost shrinks. Because total direct building cost is redistributed between labour and material, the relative material share rises. Lower labour costs also reduce detachment-related deductions.	Shifts the cost burden from labour to material, raising the material share and lowering labour and detachment costs, to increase residual value.
Carbon price on virgin materials (price-based)	Direct building cost (€)	A carbon price adds an embodied-carbon surcharge to a product's base direct building cost. The higher the product weight and embodied-carbon intensity, the larger the increase, so carbon-intensive virgin materials are penalised more than lower-carbon alternatives.	Raises the material-value base, increasing residual value, especially for high-mass, carbon-intensive materials.
Detachability Threshold - DfD (regulatory)	Detachability index [0–1]	Improves how easily a product can be removed without damage. A higher detachability score lowers expected recovery loss and reduces the detachment-cost penalty in the model.	Lower loss and lower detachment costs increase residual value; products below the detachability threshold can move from write-off to positive residual value.

5.2.1. Labour Tax Reduction (price-based Instrument)

Labour tax reduction is selected because it addresses one of the most persistent economic barriers in both the academic literature and the Dutch policy analysis: the high cost of labour-intensive circular activities such as disassembly, inspection, repair, remanufacturing, and material recovery. An important advocate of this fiscal shift is the Ex'tax Foundation, which has promoted moving taxation from labour to resource use and has contributed to the Dutch policy debate through reports commissioned by the national government.

Circular construction relies more heavily on labour than linear demolition and replacement, so a tax system that places a high burden on labour structurally disadvantages circular alternatives. Labour tax reduction works as a price-based market instrument that improves the financial viability of circular practices by shifting part of the tax burden away from labour and, in broader circular-economy terms, towards resource use (Milios, 2019; Stahel, 2016).

Because labour taxation in practice consists of multiple interacting levies, this thesis operationalises it through a single analytical proxy: employer social contributions. (Copper8, 2022) estimates this burden at roughly 21% under current Dutch conditions and explores a transition pathway reducing it to 7.4%, the range adopted in the scenario model. In reality, the labour taxation could be designed to benefit the employer as well as the employee to achieve mutual social benefits. The labour tax should be higher than 0%, to ensure government revenues in the long term.

Within the residual value methodology, the reduction is translated into changes in the labour and material cost shares of direct building cost. A lower labour share reduces labour-related detachment costs, while the corresponding rise in the material share raises the recoverable value base. The instrument therefore acts on two terms of the residual value formula at once, which is what makes it particularly relevant here. labour tax reform also affects household income and employee-side taxation, but the focus remains on the employer perspective, because the model is concerned with the financial feasibility of circular construction in project and procurement practice.

5.2.2. Carbon Pricing (price-based Instrument)

Carbon pricing is selected because it addresses a second core barrier: the structural under-pricing of virgin materials. In current construction markets, the environmental externalities of primary material production are only partially reflected in prices, which keeps carbon-intensive materials such as concrete and steel artificially competitive against bio-based and secondary alternatives. By internalising part of these external costs, carbon pricing works as a price-based market instrument that alters relative price signals and strengthens the position of lower-carbon options (Giorgi et al., 2019; Milios, 2019).

The carbon-price trajectory is derived from PBL's *Rekentool Beprijzing*, which estimates effective CO_2 pricing pathways for the Netherlands. The high-delayed scenario is selected as the most policy-relevant benchmark, reaching approximately €540 per tonne of CO_2 by 2050. PBL derives these effective CO_2 prices using a prevention-cost approach, in which the shadow price for each year reflects the cost of meeting the emission-reduction target efficiently under the relevant WLO scenario.

Within the model, carbon pricing enters as an embodied-carbon surcharge on direct building costs, so its effect depends on the mass and embodied-carbon intensity of the product: heavier, more carbon-intensive materials receive a larger increase, while lower-carbon materials such as engineered wood are affected only marginally. Carbon pricing therefore raises residual value indirectly, by lifting the material-value base from which residual value is calculated, rather than by altering detachability or recovery costs.

5.2.3. Detachability Threshold (Regulatory Instrument)

The detachability threshold is selected as a regulaotry instrument because residual value depends not only on price signals, but on whether building products can in fact be recovered without excessive damage at the end of their first use cycle. Design for disassembly is treated here as the regulatory counterpart to the two price-based instruments: where labour tax reduction and carbon pricing alter financial conditions, a detachability threshold sets a minimum design requirement for recoverability. This responds to the literature's recurring observation that without a binding requirement or strong procurement signal, end-of-life recoverability remains voluntary and is therefore neglected in design practice (Allam & Nik-Bakht, 2023; Jiang et al., 2022; Tirado et al., 2022).

Within the residual value methodology, the instrument is operationalised through the detachability index, which governs both expected material loss and detachment-cost penalties. A higher detachability score raises the likelihood that residual value can actually be realised. For the scenario design, the threshold is anchored in emerging Dutch public-sector practice, most notably the 55% benchmark adopted by the Municipality of Leeuwarden, which is used as the reference point for the regulatory scenario. Instead of percentages, this is expressed through a [0-1] scale following the format of the detachability index.

5.3. Conclusion Phase I: Selection of Policy Instruments

This chapter answers the third sub-question: which policy instruments are most suitable for incentivising residual reuse value, given the identified barriers and the variables of the theoretical residual value methodology? The selection logic is twofold. Each candidate instrument had to respond to one or more of the dominant barriers and enabling conditions identified through the literature review and the Dutch policy-document analysis in Chapter 4, and each had to correspond to a variable in the residual value methodology, so that it could be operationalised within the model introduced in Section 2.2. Three instruments are selected, a labour tax reduction, carbon pricing, and a detachability threshold.

Applying this logic shows that suitability is not a property of any instrument in isolation, but of how well an instrument fits both a specific barrier and a specific point in the residual value formula. The three selected instruments act at different stages of a building product's life and aims to tie them together, shifting production, design, procurement, and end of life and together aims through policy to redirect materials away from linear end-of-life pathways. As Milios (2017) argues, outcomes are the product of interactions between policies across a building product's life cycle, where instruments may reinforce, constrain, or complement one another.

The analysis therefore points not to a single optimal instrument but to a coordinated mix of price-based, fiscal, and regulatory instruments. Following the logic of the Policy Compass (Section 3.1.1), no preferred option is assumed in advance. The policy instrument effects (what are their impacts?) on residual reuse value across structural configurations are assessed in Chapter 7 through scenario and sensitivity analysis and expert elicitation.

6
Model Customisation

This chapter customises the scenario model used to evaluate the selected policy instruments. Building on the instruments selected in Chapter 5 and the residual value methodology introduced in Section 2.2, it specifies every component required to run the analysis: how labour tax reduction, carbon pricing, and the detachability threshold are translated into model variables, how case-study structures are converted into comparable product-level inputs, and the final scenario model design. The calculations that provide the base for these input can be found in Appendix A.

The chapter proceeds in three steps. Section 6.1 defines the policy instruments as exogenous inputs, mapping each onto the residual value parameters it acts upon and specifying the transmission pathway through which it is expected to influence residual value. Section 6.5 translates the two case-study designs into product-level model inputs, documenting the proxy assumptions required for comparability. Section 6.6 then assembles these components into the final scenario-model design — the time-based scenarios, the design-based detachability scenario, and the baseline configurations — establishing the analytical baseline from which the policy-mix analysis in the following chapter proceeds. Expert elicitation is used and reported throughout to calibrate parameter values and to test the plausibility of the model's transmission logic.

6.1. Customisation of Policy Instruments to Residual Value

This section explains how the three selected policy instruments are translated from the conceptual selection logic developed in Chapter 5 into an operational model structure. Figure 6.1 shows how the three selected incentives interact with the residual value methodology. More specifically, it shows how the selected instruments are translated to technical parameters and policy-sensitive model variables within the residual value methodology. The following figure shows how the residual value formula established in 2.2 interacts with the policy instruments.

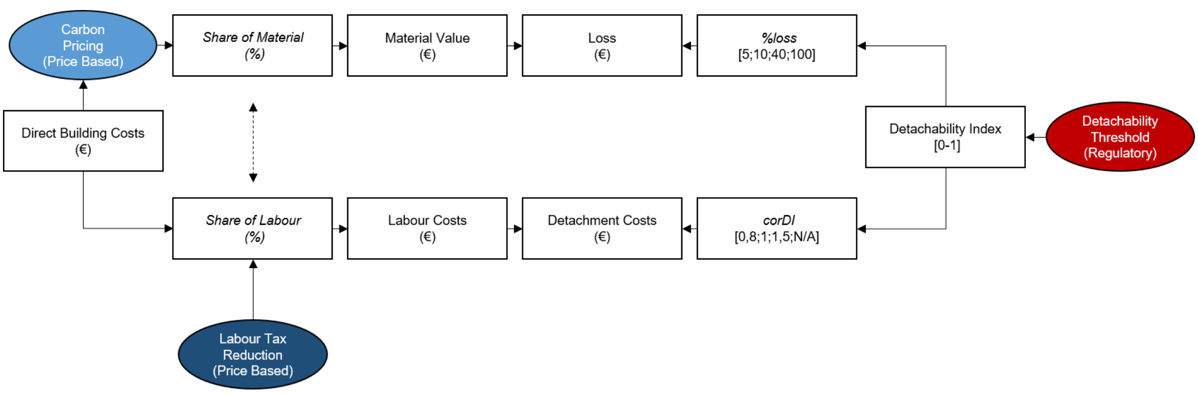

Figure 6.1: Overview of how policy instruments affect policy sensitive residual value variables

Interaction effects are expected to arise because the selected price-based instrument on partially overlapping components of the model. Interaction is mapped to occur in the material-value term: carbon pricing increases direct building cost, while labour tax reduction simultaneously shifts the costs proportion of labour to costs attributed to materials, thereby strengthening the value base from which residual value is derived. Labour tax reduction is represented through changes in the labour and material shares, and carbon pricing through an embodied-carbon surcharge on direct building costs. For the design-based scenario, the detachability threshold applies to an adjustment of the detachability index.

The scenario values are derived from sources relevant to the policy. The labour tax pathway follows the ranges proposed by (Copper8, 2022); the carbon-price trajectory follows PBL's high-delayed pathway for effective CO_2 pricing in the Netherlands; and the detachability threshold draws on emerging by Dutch procurement practice, in particular the 55% benchmark adopted by the Municipality of Leeuwarden, following the statements done by municipalities adapting theoretical residual value derived from an interview by Dutch Green Building Council (2024) . Table 5.1 summarises how each instrument enters the model and the direction of its expected effect on residual value; the three subsections that follow justify each selection in turn:

The following subsections explain the results of the customised policy instruments within the model. The aim is to illustrate how the selected instruments enter the residual value model as exogenous inputs. It establishes the analytical pathways through which labour tax reduction, carbon pricing, and a detachability threshold are expected to influence residual reuse value. Expert elicitation was used to assess parameter and model assumptions, whenever the model required refining of scenario plausibility and transmission logic this was applied and noted. The expert elicitation provided the validation for the scenario model's policy instruments variables function as exogenous inputs, these findings can be found in Appendix C, and are summarised in C.1.3.

6.2. Labour Tax Customisation

To assess the impact of labour taxation on the residual value of building components, changes in labour taxation are operationalised through a labour tax multiplier, denoted as $\tau_{L,\text{multiplier}}$. This multiplier adjusts the relative distribution between labour and material cost shares within direct building costs, thereby influencing detachment costs (DC) and recoverable material value (Vmat) calculations.

6.2.1. Labour Tax Multiplier

The labour tax multiplier is defined as:

$$\tau_{L,\text{multiplier}} = \frac{1 + t_{L,x}}{1 + t_{L,0}} \tag{6.1}$$

where:

- $t_{L,x}$: labour tax rate in scenario x
- $t_{L,0}$: baseline labour tax rate

This formulation captures the proportional change in labour taxation relative to the baseline scenario.

6.2.2. Adjustment of Cost Shares

The labour share in scenario x is adjusted using the labour tax multiplier:

$$\%labour_x = \%labour_0 \cdot \tau_{L,\text{multiplier}} \tag{6.2}$$

where:

- $\%labour_0$: baseline labour share of direct building costs
- $\%labour_x$: adjusted labour share in scenario x

To ensure consistency in the cost structure, total direct building costs are assumed to remain constant. Therefore, a decrease in labour share is offset by a corresponding increase in material share:

$$\%material_x = \%material_0 + (\%labour_0 - \%labour_x) \tag{6.3}$$

where:

- $\%material_0$: baseline material share
- $\%material_x$: adjusted material share in scenario x

6.2.3. Customisation of Labour Costs

The adjusted labour share is translated into labour costs as follows:

$$C_{\text{labour},x} = \%labour_x \cdot DirectBuildingCosts_0 \tag{6.4}$$

where:

- $DirectBuildingCosts_0$: baseline direct building costs
- $C_{\text{labour},x}$: labour costs in scenario x

Importantly, the model uses baseline direct building costs ($DirectBuildingCosts_0$) as a fixed reference point. Expert elicitation indicated that increases in direct building costs do not necessarily translate proportionally into higher labour costs (Appendix C). Holding this value constant therefore avoids overstating the effect of cost escalation on labour-intensive processes.

6.2.4. Detachment Costs

Labour cost adjustments directly influence detachment costs, which are assumed to be primarily labour-driven:

$$DetachmentCosts_x = C_{\text{labour},x} \cdot corDI_x \tag{6.5}$$

where:

- $corDI_x$: correction factor linked to the detachability index in scenario x
- $DetachmentCosts_x$: detachment costs in scenario x

6.2.5. Interpretation

A reduction in labour taxation ($t_{L,x} < t_{L,0}$) decreases the labour tax multiplier, resulting in a lower labour cost share and a corresponding increase in material share. This reduces labour-dependent detachment costs and improves the economic viability of material recovery.

6.3. Carbon Pricing Customisation

To account for the impact of carbon pricing on the residual value of building materials, carbon costs are incorporated through an adjustment of baseline direct building costs. This approach reflects how embodied emissions translate into additional financial costs under a given carbon pricing regime.

6.3.1. Carbon Cost Adjustment

Carbon pricing is customised as an additive cost component to baseline direct building costs. This formulation translates embodied emissions into a direct monetary cost, thereby internalising environmental externalities within the model:

$$DirectBuildingCosts_x = DirectBuildingCosts_0 + \left(W \cdot EC \cdot \frac{p_{CO_2}}{1000}\right) \tag{6.6}$$

where:

- $DirectBuildingCosts_0$: baseline direct building costs
- $DirectBuildingCosts_x$: adjusted direct building costs in scenario x

- W: material weight (kg)
- EC: embodied carbon intensity (kgCO_2eq/kg)
- p_{CO_2}: carbon price (€/tonne CO_2eq)

Because embodied carbon $W \cdot EC$ is expressed in kgCO_2eq while the carbon price p_{CO_2} is set per tonne, the price is divided by 1000 to convert it to €/kgCO_2eq before it is applied.

6.3.2. Embodied Carbon Assumptions

Material-specific embodied carbon values are applied to ensure consistent comparison across scenarios. These values represent typical emission intensities per kilogram of material. However, it is important to note that embodied carbon is highly dependent on production methods, supply chains, and technological factors.

Expert elicitation indicated that there was no complete agreement on precise embodied carbon values, highlighting a degree of uncertainty in these parameters. As such, embodied carbon is treated as a key source of model uncertainty and is explicitly tested in the sensitivity analysis (see Figure 7.13).

Up-to-date Dutch reference values were derived from van Oostveen (2026), ensuring alignment with national datasets and current practice.

Table 6.1: Embodied carbon intensity values applied per structural material (derived from van Oostveen (2026)).

Material	**Embodied carbon (kgCO_2eq/kg)**
Reinforced concrete	0.90
Structural steel	2.30
Engineered wood	0.10

6.3.3. Interpretation

An increase in carbon price (p_{CO_2}) leads to a proportional increase in direct building costs, depending on the embodied carbon intensity and material weight. Materials with higher embodied carbon intensities, such as structural steel and reinforced concrete, are therefore more strongly affected.

By internalising carbon costs into the economic model, this mechanism captures the effect of climate policy instruments on material selection and cost structures. Higher carbon pricing can reduce the relative attractiveness of high-emission materials and thereby influence the residual value of building components.

The inclusion of embodied carbon also enables the model to assess trade-offs between environmental performance and economic outcomes, supporting an integrated evaluation of circular construction strategies.

6.4. Detachability Threshold Customisation

The detachability (*DfD*) threshold is analysed as a technical design intervention rather than as part of the price-based interaction. It is a regulatory instrument where expert elicitation established no causal relationship between the price-based instruments and the detachability index: lowering labour tax or raising carbon price does not, in itself, affect detachbility. Detachability is therefore modelled as an independent design parameter.

Expert elicitation informed the upper bounds applied in DfD-1, which can be found in the Appendix C.3. For the reinforced concrete floor, experts warned that assuming substantially higher detachability would likely overestimate practical reuse potential, because concrete elements can become highly specific and therefore difficult to re use in future projects. For that reason, the DfD-1 value for the hollow-core slab is capped at 0.25. By contrast, the DfD-1 value of 0.55 for the steel structure follows the detachability target.

6.4.1. Interpretation

The detachability threshold functions as a key technical lever that directly influences the recoverability of building materials, which influence the technical cycle defined in 2.1.1. While price-based instruments such as labour tax reductions and carbon pricing affect cost structures, they do not alter the inherent design characteristics that determine whether materials can be effectively disassembled and reused.

6.5. Case Studies Customisation

This section explains how the two case studies are translated into model inputs. For each case, the structural design is reduced to the main load-bearing products analysed in the thesis: floor slabs and the structural frame (beams and columns). Where no exact product match is available in the dataset, transparent proxy assumptions were used and documented in Appendix B. The aim is to create comparable and reproducible inputs for the policy-mix analysis.

6.5.1. Case Study 1 Office

Case Study 1 is a new office building with an engineered-wood structure and a concrete core. The building has three storeys and a total floor area of 1,420 m^2. The data is derived from the analysis of WSP Nederland B.V. (2023), where two structural design variants are compared: a bio-based engineered-wood design and a conventional steel reference design (Tables 6.2 and 6.3).

Table 6.2: Case Study 1 — engineered-wood variant: glulam structure with CLT floor slabs.

Material	%Mat.	%Lab.	DB (€)	DI
CLT floor 200 mm	76%	10%	297,928	0.81
Glulam structure	50%	44%	46,610	0.81
Steel structure	44%	38%	87,110	0.27

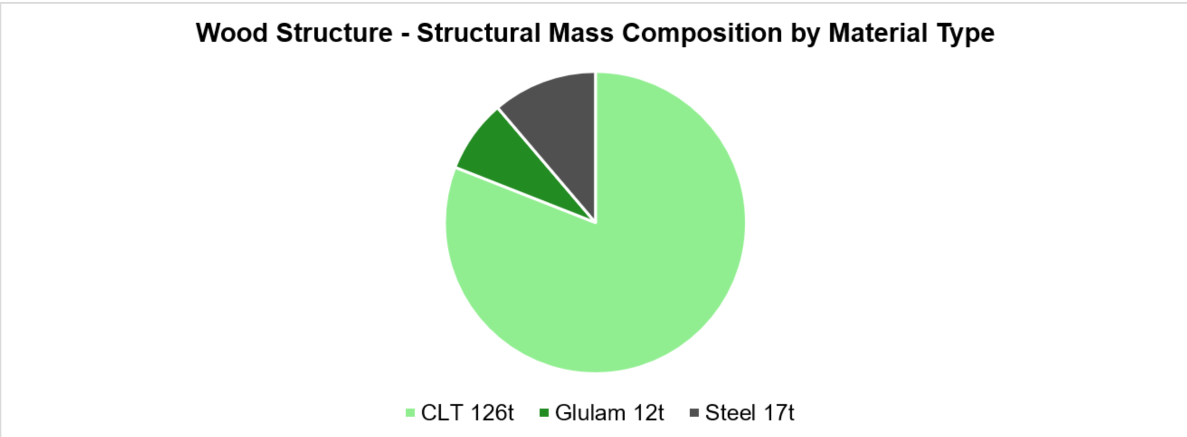

Figure 6.2: Mass composition of the wood structure in tonnes

Table 6.3: Case Study 1 — steel reference variant: steel structure with hollow-core reinforced concrete floors.

Material	%Mat.	%Lab.	DB (€)	DI
RC floor 200 mm	70%	30%	101,536	0.16
Steel structure	44%	38%	221,045	0.27

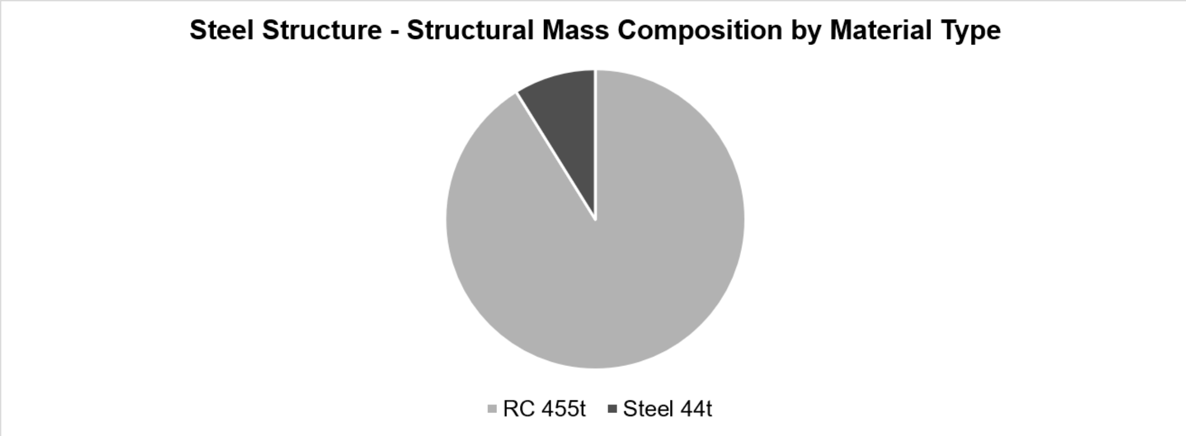

Figure 6.3: Mass composition of the steel structure in tonnes

6.5.2. Case Study 2 School

Case Study 2 is a primary school in Amsterdam with a gross floor area of 3,449 m^2, combining a primary school, daycare, and a sports facility. Two structural variants are analysed — a traditional design and a circular design — with input data gathered during expert interviews (E1 from Appendix C.3 (Tables 6.4 and 6.5).

Table 6.4: Case Study 2 traditional variant: steel frame with a hollow-core reinforced concrete floor.

Material	%Mat.	%Lab.	DB (€)	DI
RC floor 320 mm	75%	25%	317,308	0.16
Steel structure	44%	38%	525,065	0.27

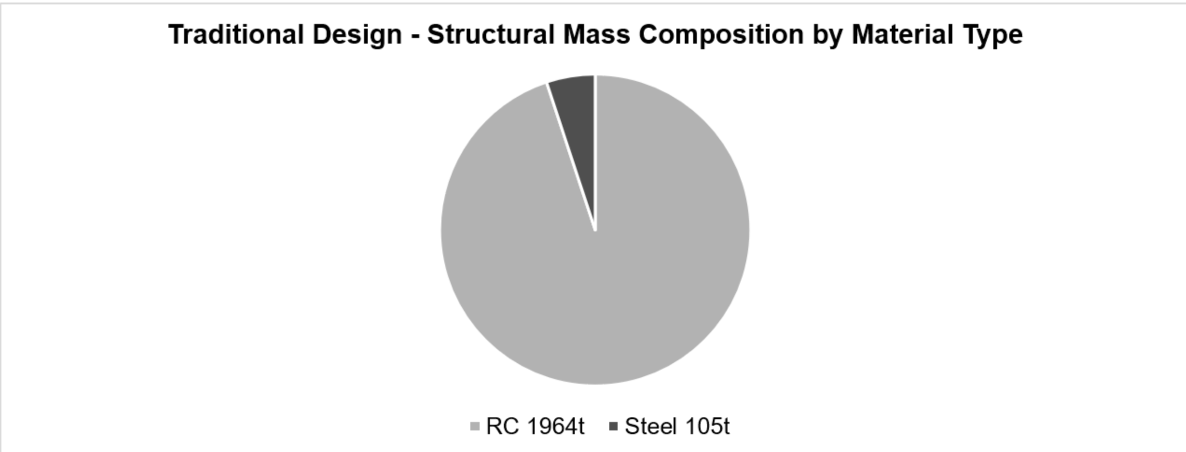

Figure 6.4: Mass composition of the traditional design in tonnes

Table 6.5: Case Study 2 circular variant: glulam frame, a detachable hollow-core reinforced concrete floor on the ground floor, and CLT floors on the upper levels.

Material	%Mat.	%Lab.	DB (€)	DI
CLT floor 320 mm	79%	7%	932,240	0.81
Glulam structure	50%	44%	116,604	0.81
RC floor, DfD-improved 320 mm	75%	25%	81,730	0.25
Steel structure	44%	38%	105,015	0.27

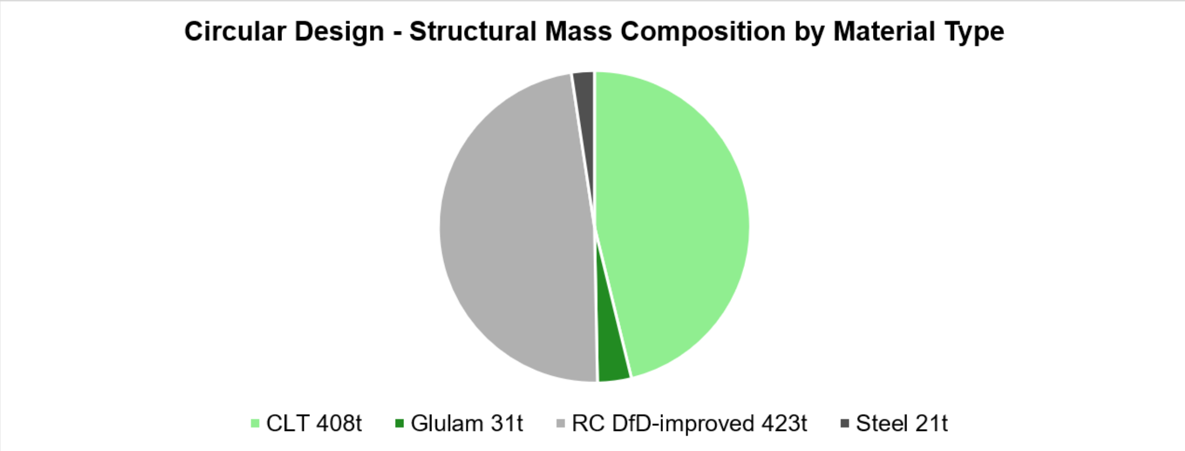

Figure 6.5: Mass composition of the circular design in tonnes

6.6. Final Scenario Model Design

The scenario model operationalises a transition pathway from a linear to a circular economic system through four time-based scenarios, from 2026 (S0) to 2050 (S3), and applies the design scenario separately (DfD-0 to DfD-1). Table 6.6 presents the base residual value for all four structural configurations across the two case studies; it serves as the analytical baseline from which the scenario analysis proceeds.

Table 6.6: Base residual value and material composition of the four analysed case-study structures, forming the analytical baseline for the scenario analysis.

Structure	Base RV (€)	Material composition
CS1 Wood structure	158,884	Bio-based dominant
CS1 Steel structure	−93,015	Conventional
CS2 Traditional design	−220,946	Conventional
CS2 Circular design	663,460	Mixed (conventional detachable design + bio-based dominant)

The scenario model compares four structural configurations across the two case studies. Within each case, the analysis distinguishes structural building products by element category — floor slabs and structural frames (beams and columns) — and by material typology, namely structural steel, reinforced concrete, and engineered wood (glulam and CLT). This design makes it possible to attribute changes in residual reuse value to individual policy instruments as well as to their combined operation across contrasting structural material configurations.

The price-based instruments are run under three conditions: (1) labour tax reduction, (2) carbon pricing, and (3) the combined price-based policy mix. The corresponding time-based parameter values are given in Table 6.7.

Table 6.7: Time-based scenario parameters for the price-based instruments, from 2026 (S0) to 2050 (S3).

Scenario	Year	Labour tax (%)	Carbon price (€/tonne CO_2)
S0	2026	21.0%	310
S1	2030	18.3%	343
S2	2040	12.9%	432
S3	2050	7.4%	540

The detachability threshold is applied separately as a technical redesign, raising each product's Detachability Index from its baseline (DfD-0) to an improved value (DfD-1), as shown in Table 6.8.

Table 6.8: Product-specific DI values applied across the design-based scenarios DfD-0 to DfD-1.

Structural building product material	DfD-0	DfD-1
Structural steel (beams and columns)	0.27	0.55
Reinforced concrete floor (floor slabs)	0.16	0.25

7
Evaluation of Policy Instruments

This chapter presents the results of the policy-mix analysis. It proceeds in three analytical blocks. First, the price-based instruments are applied to the base configuration of the case studies (Section 7.1), followed by the regulatory instrument applied in isolation (Section 7.2). The individual effects are then compared directly (Section 7.3). Subsequently, the price-based instruments are applied under improved detachability (Section 7.4) to examine interactions between regulatory and price-based levers. Model sensitivity is assessed through a deterministic sensitivity analysis (Section 7.7), followed by validation through expert elicitation (Section 7.6). Finally, the results are evaluated against four criteria (Section 7.8), addressing sub-question 4: *How do the selected price-based instruments (labour-tax reduction and carbon pricing) and the regulatory instrument (a detachability threshold) affect the residual reuse value of structural building materials, individually, in combination, and relative to one another across material typologies?*

Two case studies anchor the analysis: an office building (Case Study 1) and a primary school (Case Study 2), each comparing conventional and more circular structural configurations. Their base residual values are summarised in Table 7.2. Scenario values run across four time steps, S0 (2026) to S3 (2050); the full year-by-year residual values for every structure and scenario are reported in Appendix D, while the chapter body presents the trajectories graphically and the totals in summary form. Detailed mass-based material composition ratios are provided in Chapter 6.5, where the distribution of structural materials per configuration is visualized through graphs. Table 7.1 gives an overview of the structural configurations and their material composition.

Table 7.1: Material composition classification of the analysed structural configurations

Case study	Structure	Material composition
1 Office	Wood structure	Bio-based dominant
1 Office	Steel structure	Conventional
2 School	Traditional design	Conventional
2 School	Circular design	Mixed (detachable + bio-based)

The base values show variation in scale for residual value and are deterministic across case studies and structures. Absolute values are influenced by scale differences, while the RV/DB ratio normalises these effects, enabling consistent comparison. Consequently, policy impacts are more robustly interpreted through changes in RV/DB rather than only on absolute residual values.

Table 7.2: Base direct building costs and residual value of the four analysed structural configurations across two case studies in the base scenario (S0, 2026)

Case study	Structure	DB 2026 (€)	Base RV (€)	RV/DB (%)
1 Office	Wood structure	431,648	158,884	36.8%
1 Office	Steel structure	322,581	-93,015	-28.8%
2 School	Traditional design	842,373	-220,946	-26.2%
2 School	Circular design	1,235,589	663,460	53.7%

7.1. Results price-based Instruments under Base Detachability

The price-based instruments, a labour tax reduction (τ_L) and carbon pricing (p_{CO_2}), were applied across the four scenario years to each structure at its base detachability. The absolute values per policy scenario in years can be found in D. Table 7.3 reports the full effect: the total increase each instrument has on the residual value of a structural configuration, the combined effect, and the interaction between S0 and S3. Across all configurations, labour tax reduction is the stronger price lever and carbon pricing the weaker, with one exception. Interaction effects between the price-based instruments are positive but limited.

Case Study 1 'Office' The wood structure's residual value in figure 7.1 increases from €158,884 to €179,356 under the combined pathway, of which labour tax explains €16,873 and carbon pricing only €3,437. The reference steel structure in figure 7.2 follows the same pattern in relative terms — labour tax €17,260 against carbon pricing €3,087 — but remains negative throughout, moving only from €-93,015 to €-72,370. Price signals raise the level of residual value but do not lift the steel structure across the threshold from write-off to recoverable material.

Table 7.3: Residual value increase from price-based instruments for Case Study 1 (Office) at base detachability (DfD-0).

Case Study 1	τ_L (€)	Share (%)	p_{CO_2} (€)	Share (%)	Combined (€)
Wood structure	16,873	82.4	3,437	16.8	20,472
Steel structure	17,260	83.6	3,087	14.9	20,645

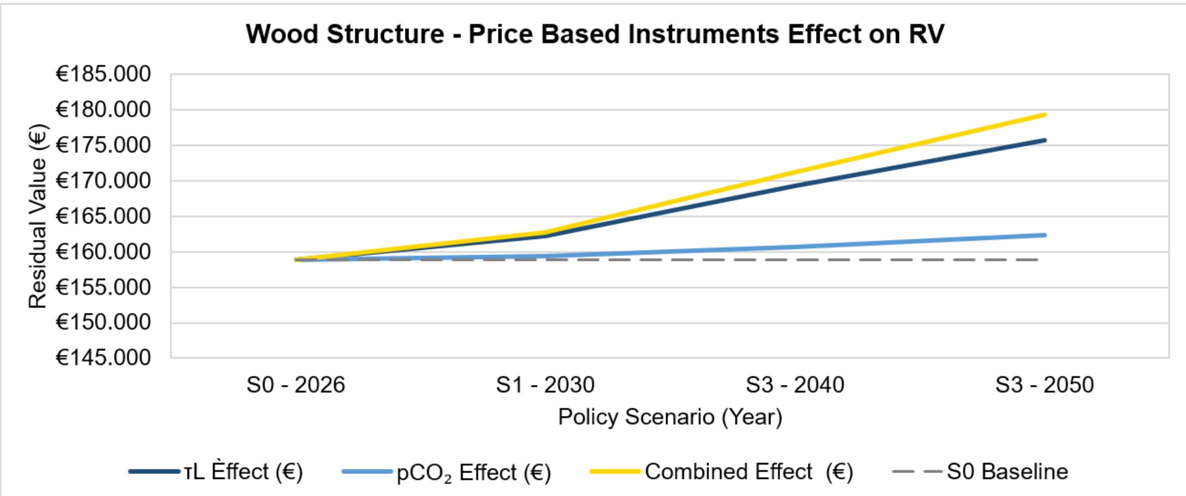

Figure 7.1: Residual value development under price-based instruments for the wood structure in Case Study 1 (Office) at base detachability (DfD-0).

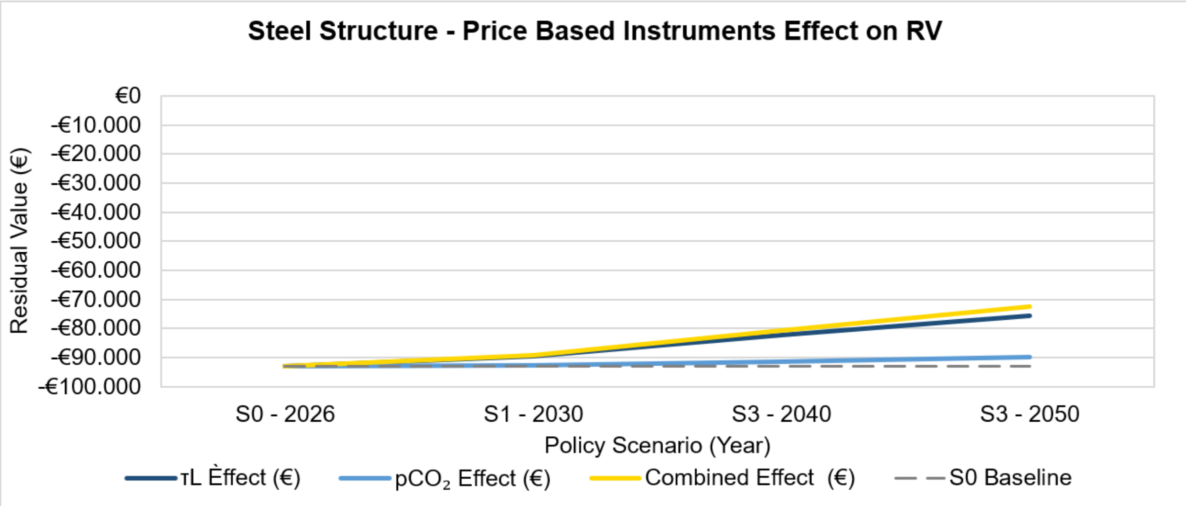

Figure 7.2: Residual value development under price-based instruments for the steel structure in Case Study 1 (Office) at base detachability (DfD-0).

Case Study 2 'School' Absolute gains are larger, reflecting a bigger project scale, higher structural mass, and higher direct building costs. For the traditional structure, labour tax again dominates, contributing €41,000 compared to €7,333 from carbon pricing. The combined increase of €49,039 nevertheless leaves the structure negative at €-171,907, indicating that price signals alone remain insufficient to overcome structural value losses.

The circular design forms a key exception. Here, carbon pricing becomes the primary driver, contributing €48,094 compared to €37,422 from labour tax. This reversal is explained by the presence of a high-mass, detachable reinforced-concrete floor, which is both carbon-intensive and responsive to detachment improvements. As a result, it is more exposed to the embodied carbon surcharge than the lighter, low-carbon CLT floors.

Table 7.4: Residual value increase from price-based instruments for Case Study 2 (School) at base detachability (DfD-0).

Case Study 2	τ_L (€)	Share (%)	p_{CO_2} (€)	Share (%)	Combined (€)
Traditional design	41,000	83.6	7,333	14.9	49,039
Circular design	37,422	42.9	48,094	55.1	87,250

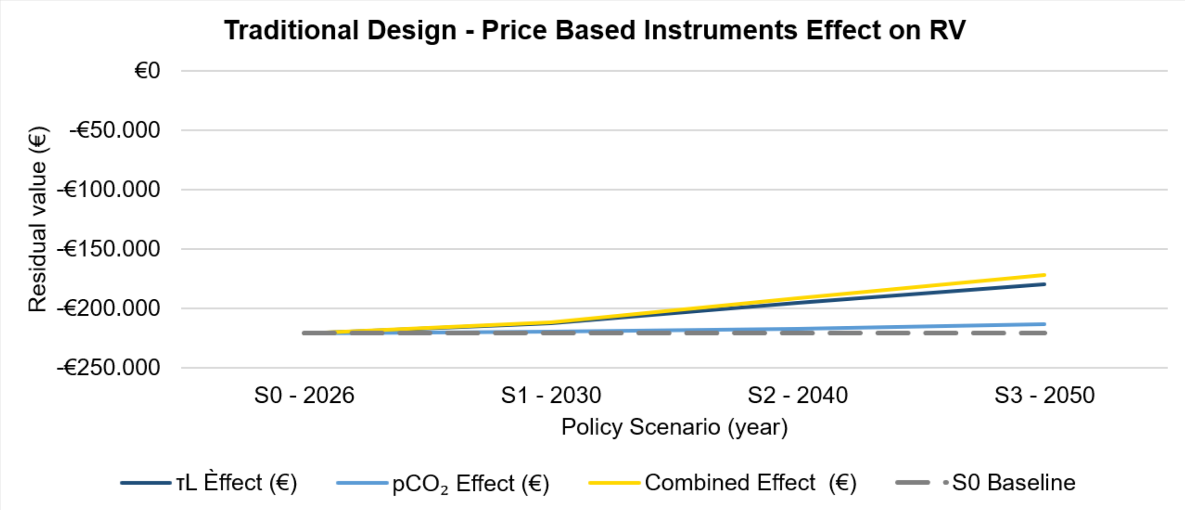

Figure 7.3: Residual value development under price-based instruments for the traditional structure in Case Study 2 (School) at base detachability (DfD-0).

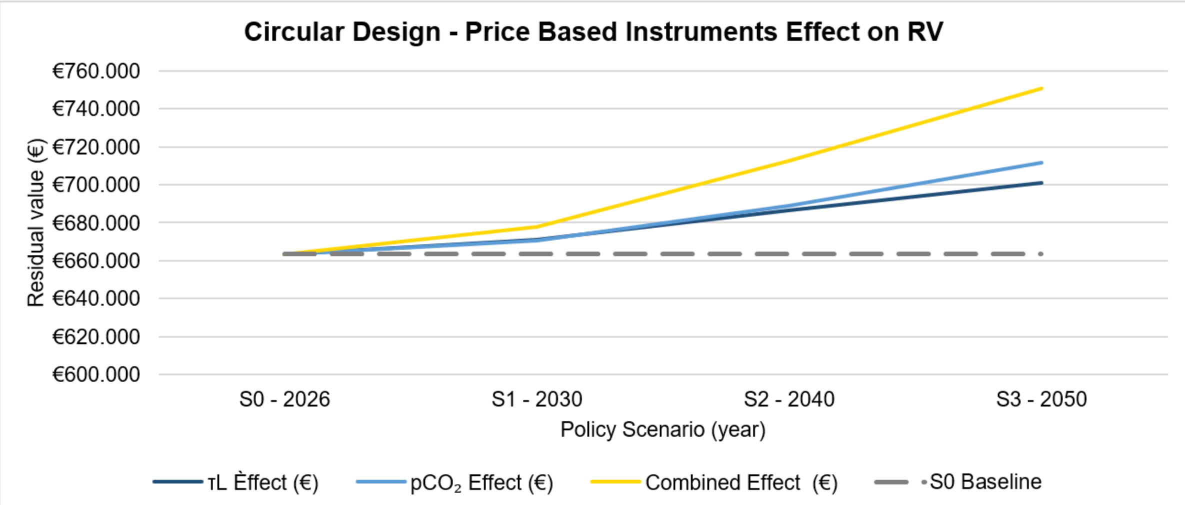

Figure 7.4: Residual value development under price-based instruments for the circular structure in Case Study 2 (School) at base detachability (DfD-0).

Across both case studies, the results indicate that labour tax reductions generally provide the strongest and most consistent increase in residual value. However, carbon pricing can become the leading lever where three conditions coincide: high material mass, high embodied carbon intensity, and sufficient detachability. In such configurations, carbon pricing shifts from a marginal contributor to a more dominant driver of residual value increase.

The interaction effect between the two price instruments is positive but negligible across all case studies and structural configurations, between €162 and €1,735, or under two percent of the combined effect, indicating they act largely independent.

Table 7.5: Interaction effects between labour tax and carbon pricing at base detachability (DfD-0).

Case study	Structure	Interaction (€)	Relative effect (%)
1 Office	Wood structure	162	0.8
1 Office	Steel structure	297	1.4
2 School	Traditional design	706	1.4
2 School	Circular design	1,735	2.0

7.2. Results Regulatory Instrument

The detachability threshold behaves differently from the price-based instruments: it changes whether residual value can be realised at all, rather than adjusting its level. Improving detachability from the base condition (DfD-0) to the threshold condition (DfD-1) produces the shifts in Table 7.6.

Table 7.6: Residual value at base (DfD-0) and improved (DfD-1) detachability, including absolute increase.

Case study	Structure	DfD-0 (€)	DfD-1 (€)	Increase (€)
1 Office	Wood structure	158,884	188,443	29,559
1 Office	Steel structure	-93,015	18,618	111,633
2 School	Traditional design	-220,946	164,421	385,367
2 School	Circular design	663,460	699,094	35,634

The results indicate distinct differences between configurations. Improving detachability shifts the Case Study 1 steel structure from €-93,015 to a positive €18,618, which is visualised in figure 7.5. For Case Study 2, the traditional design from €-220,946 to €164,421, visualised in figure 7.6, in both cases the conventional material dominant structure crosses the line from write-off to recoverable asset.

For the already detachable designed or bio-based material dominant structures the effect is minor: the Case Study 1 wood structure gains €29,559 (figure 7.5). For Case Study 2, the circular design gains only €35,634 (figure 7.6). because both already sit well above the detachability gate. Detachability therefore functions as a threshold condition for conventional material dominant structures, illustrating the advantage of bio-based materials and detachable design.

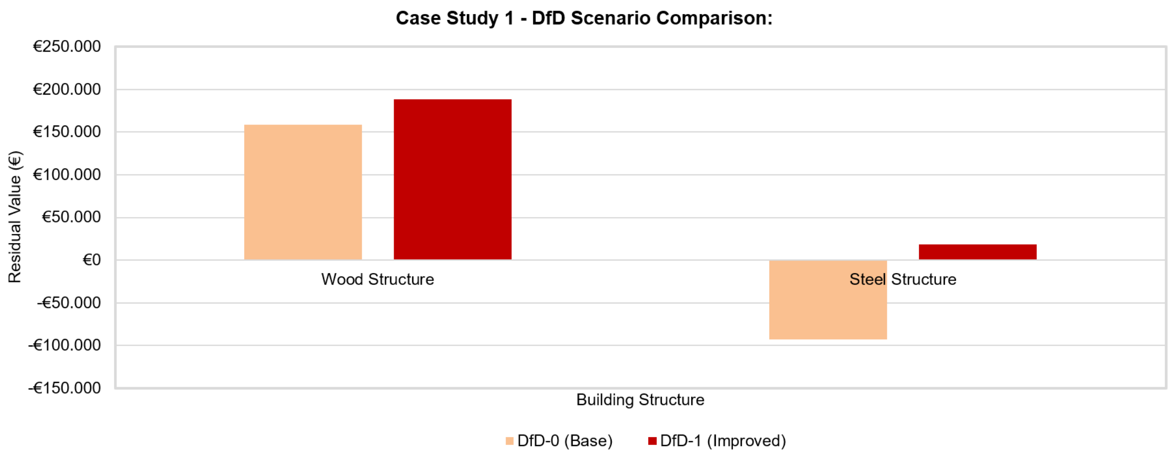

Figure 7.5: Residual value under base (DfD-0) and improved detachability (DfD-1) for structural configurations in Case Study 1 (Office).

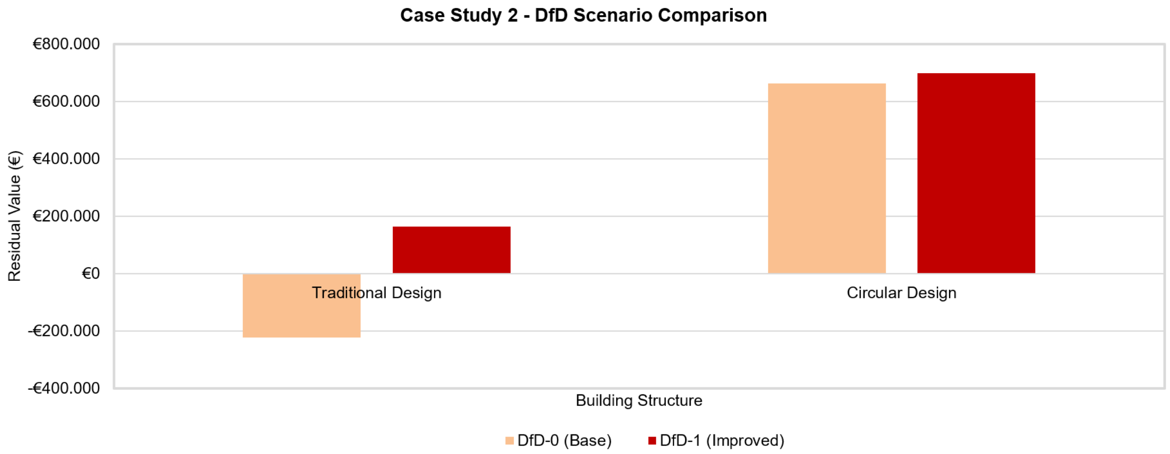

Figure 7.6: Residual value under base (DfD-0) and improved detachability (DfD-1) for structural configurations in Case Study 2 (School).

7.3. Results Individual Effects of Policy Instruments

Tables 7.7 and 7.8 place the three instruments' total effects side by side, making the structure of the result explicit: labour tax leads among the price instruments, while detachability dominates overall magnitude for the conventional structures. Note, the figures below show the total increase of residual value, from S0 - 2026 to S3 - 2050.

Table 7.7: Total effect of each policy instrument on the residual value of the structural configuration of case study 1

Case Study 1 Office	τ_L (€)	p_{CO_2} (€)	*DfD* (€)
Wood structure	16,873	3,437	29,558
Steel structure	17,260	3,087	111,633

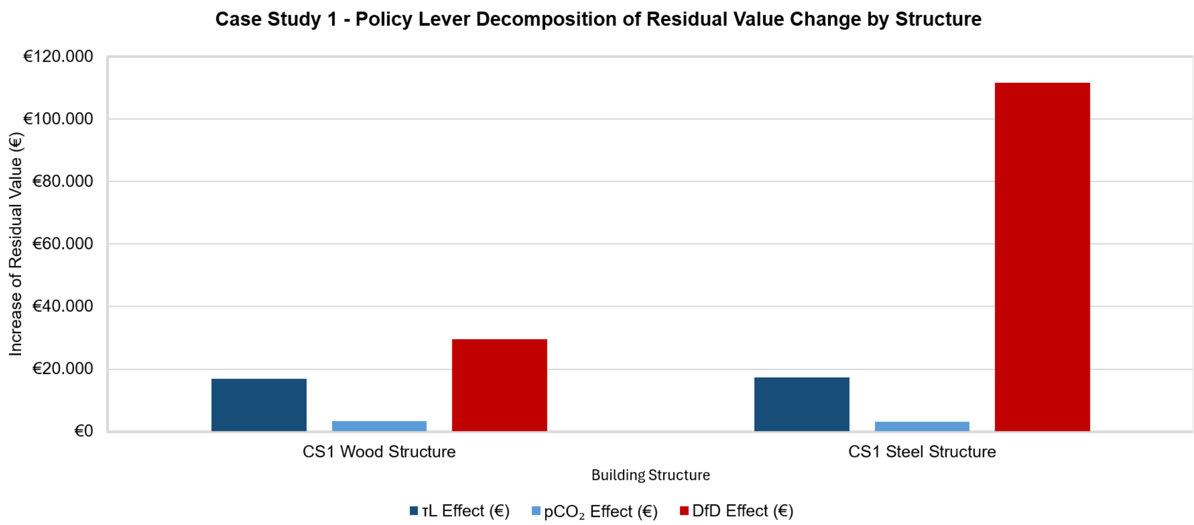

Figure 7.7: Relative contribution of individual policy instruments to residual value for structural configurations in Case Study 1 (Office).

Table 7.8: Total effect of each policy instrument on the residual value of the structural configuration of case study 2.

Case Study 2 School	τ_L **(€)**	p_{CO_2} **(€)**	*DfD* **(€)**
Traditional design	41,000	7,333	385,367
Circular design	37,422	48,094	35,634

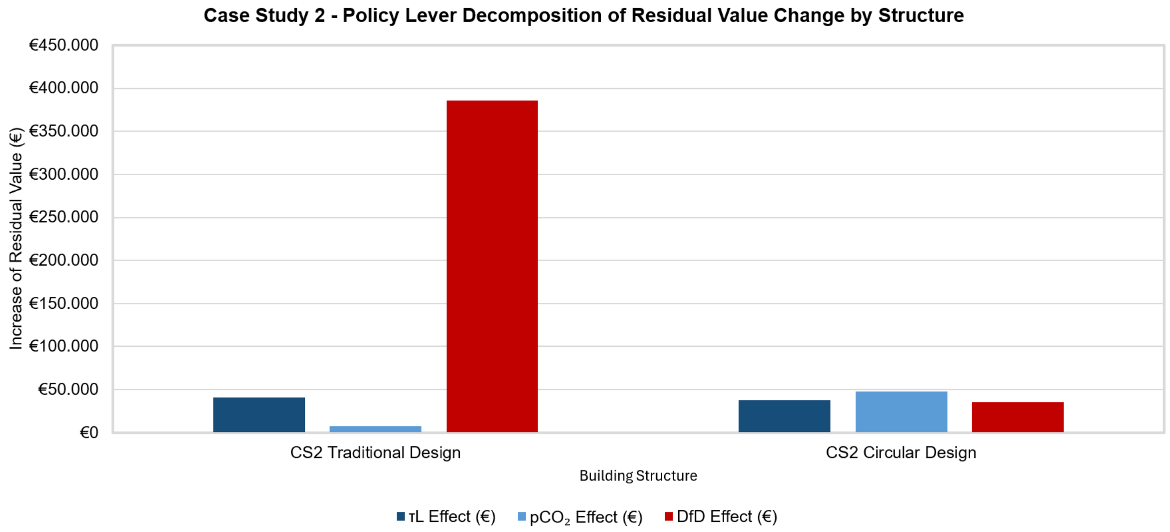

Figure 7.8: Relative contribution of individual policy instruments to residual value for structural configurations in Case Study 2 (School).

For conventional material dominant structure (steel structure, traditional design), the detachability threshold is the dominant driver, 5 to almost 8 times the combined price-based instrument effect. For the already detachable designed structure, circular design, detachability is the weakest lever, because there is no write-off gate left to open.

When looking at the individual effect of the price-based instruments, the results indicate labour tax as the most influential policy instrument. In one example, the circular design of case study 2, the full effect of carbon pricing on the RV exceeds the full effect of a labour tax reduction. This indicates carbon pricing is more effective when high mass detachable reinforced concrete floors are incorporated in the design.

7.4. Results price-based Instruments under Improved Detachability

Applying the price instruments again, this time on the improved-detachability (DfD-1) baseline, provides the interaction between the regulatory and the price-based instruments. Note, only improving detachability from the base condition (DfD-0) to the threshold condition (DfD-1) produces the shifts in Table 7.6 The absolute values per policy scenario in years can be found in appendix D.2.

Case Study 1 (Office). Under improved detachability (DfD-$_1$), the effect of price-based instruments changes substantially for the steel structure. The wood structure remains primarily driven by labour tax reduction, which accounts for 76.8% of the combined residual value increase. Carbon pricing contributes 21.9%, indicating that the low embodied-carbon intensity of the wood structure limits its exposure to carbon pricing.

For the steel structure, however, carbon pricing becomes the dominant driver. It contributes €45,827, or 62.1% of the combined increase, compared to €25,516 from labour tax. This shows that once detachability is improved, the high embodied-carbon intensity and higher material mass of steel make carbon pricing a much stronger residual value lever.

Table 7.9: Total residual value increase from price-based instruments for Case Study 1 (Office) (S0 (2026)→S3 (2050)) at improved detachability (DfD-1), including relative contribution shares.

Structure	τ_L (€)	Share (%)	p_{CO_2} (€)	Share (%)	Combined (€)
Wood structure	16,293	76.8	4,653	21.9	21,225
Steel structure	25,516	34.5	45,827	62.1	73,838

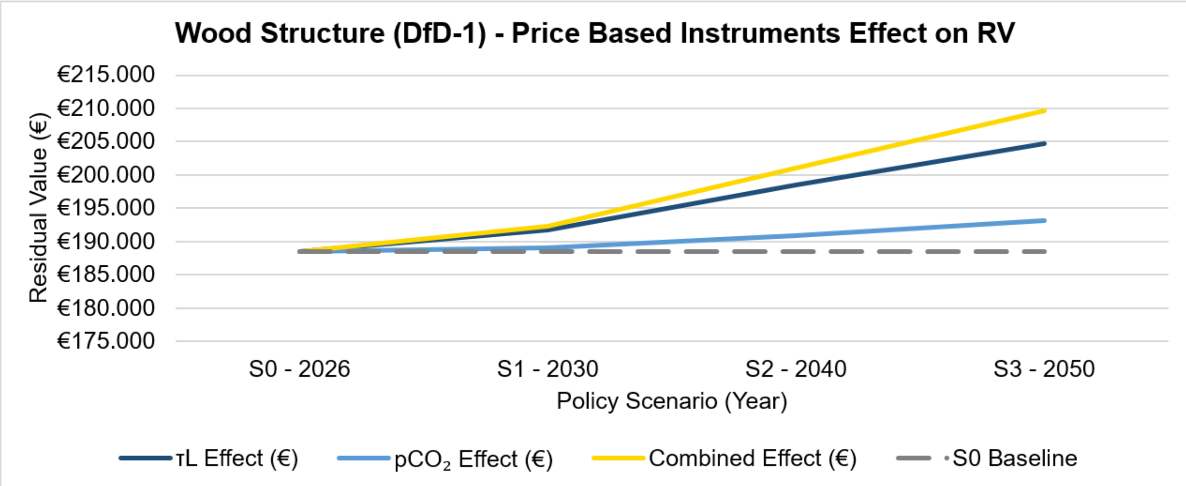

Figure 7.9: Residual value development under price-based instruments for the wood structure in Case Study 1 (Office) at improved detachability (DfD-1).

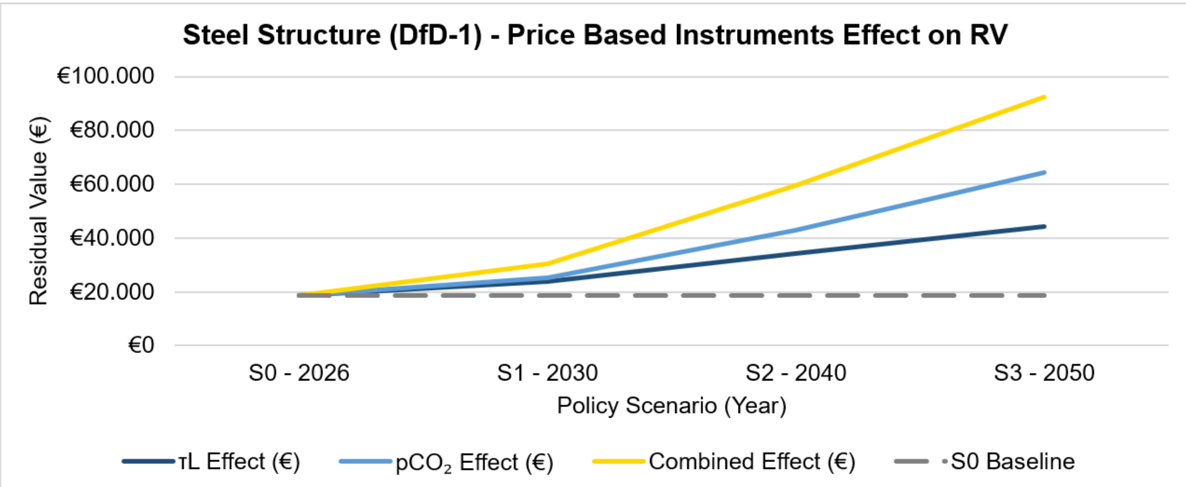

Figure 7.10: Residual value development under price-based instruments for the steel structure in Case Study 1 (Office) at improved detachability (DfD-1).

Case Study 2 (School). The same pattern becomes even more pronounced in Case Study 2. For the traditional design, carbon pricing becomes the dominant policy instrument under improved detachability, contributing €196,836, or 72.6% of the combined increase. Labour tax contributes €65,797, equal to 24.3%. This confirms that improved detachability allows high-mass, carbon-intensive conventional materials to respond more strongly to carbon pricing.

The circular design also remains more strongly influenced by carbon pricing than by labour tax, although the difference is smaller. Carbon pricing contributes €49,560, or 56.2%, while labour tax contributes €36,723, or 41.7%. This reflects the mixed material composition of the circular design: it already benefits from improved detachability, while still containing carbon-intensive material components that remain exposed to carbon pricing.

Table 7.10: Total residual value increase from price-based instruments for Case Study 2 (School) at improved detachability (DfD-1), including relative contribution shares.

Structure	τ_L (€)	Share (%)	p_{CO_2} (€)	Share (%)	Combined (€)
Traditional design	65,797	24.3	196,836	72.6	270,980
Circular design	36,723	41.7	49,560	56.2	88,159

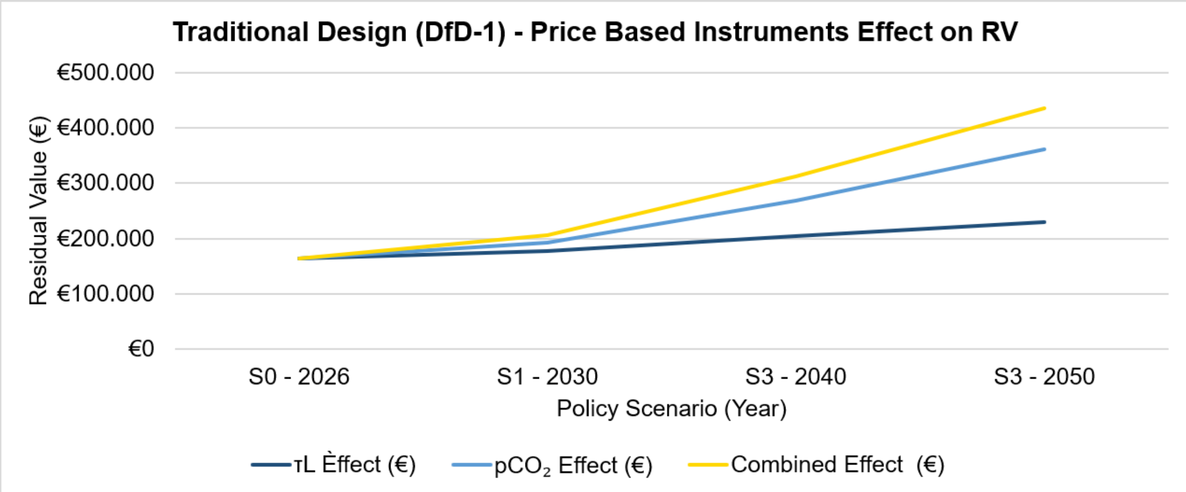

Figure 7.11: Residual value development under price-based instruments for the traditional structure in Case Study 2 (School) at improved detachability (DfD-1).

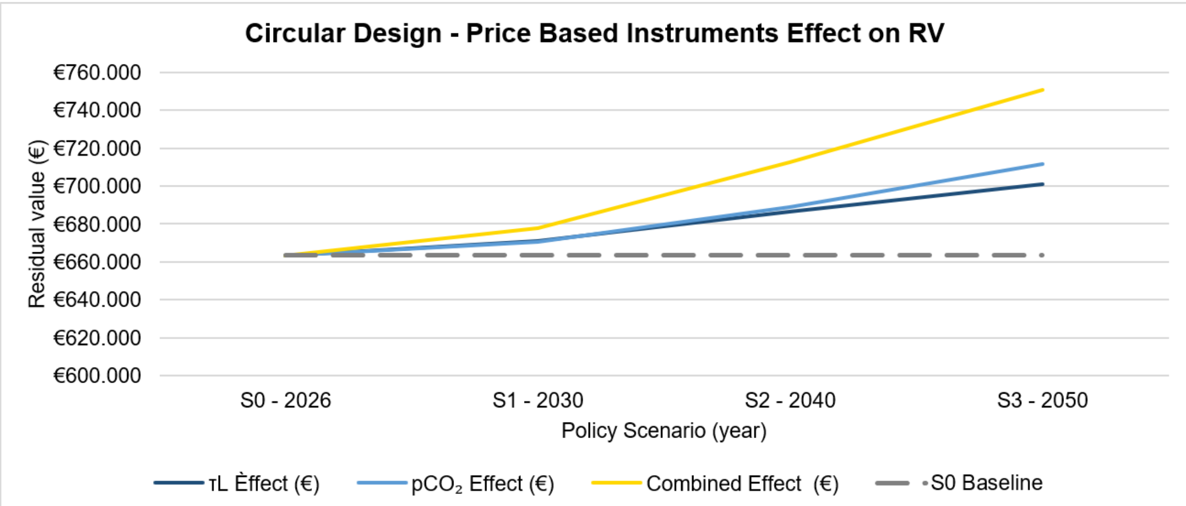

Figure 7.12: Residual value development under price-based instruments for the circular structure in Case Study 2 (School) at improved detachability (DfD-1).

Across both case studies, improved detachability changes the relative effectiveness of the price-based instruments. At base detachability, labour tax reductions generally provide the strongest and most consistent increase in residual value. Under improved detachability, however, carbon pricing becomes dominant for high-mass and carbon-intensive structures, particularly the steel structure in Case Study 1 and the traditional design in Case Study 2.

This indicates that detachability does not merely increase residual value directly, but also improves the effectiveness of carbon pricing as a policy instrument. Once materials become technically recoverable, embodied-carbon surcharges translate more strongly into residual value improvements. Labour tax remains relevant, especially for wood and mixed circular designs, but carbon pricing becomes the leading lever where high material mass, high embodied-carbon intensity, and sufficient detachability coincide.

The interaction effect between labour tax and carbon pricing remains positive but limited. At improved detachability, interaction effects range from €279 to €8,347, corresponding to 1.3–3.4% of the combined effect. This result also indicates that the two price-based instruments operate largely additively rather than synergistically, even when detachability is improved.

Table 7.11: Interaction effects between labour tax and carbon pricing at improved detachability (DfD-$_1$).

Case study	Structure	Interaction (€)	Relative effect (%)
1 Office	Wood structure	279	1.3
1 Office	Steel structure	2,496	3.4
2 School	Traditional design	8,347	3.1
2 School	Circular design	1,876	2.1

7.5. Residual Value to Investment Ratios

Absolute residual value effects alone do not capture how a structure converts investment into recoverable value. Residual value is also expressed as a relative percentage of the initial costs. This relative indicator captures the proportion of value that is retained at the end-of-life (EoL) stage, enabling comparison across materials and scenarios and it is the base for circular depreciation. As valuation practice, the residual value is represented as either an percentage of the initial investment (Jiang et al., 2022). The ratio of residual value to investment (RV/DB), in this research direct building cost, provides this measure, where all absolute values can be found in Appendix D.3.

The before-and-after columns of Table 7.12 shows this ratio, before the pricebased instruments and after the pricebased instruments under different detachability scenario (DfD-0 and DfD-1). For the wood structure, the RV/DB ratio increases following the price instruments (from 36.8% to 38.9% at base detachability): the low embodied-carbon factor of CLT leaves direct building cost largely unchanged, so the residual value gain translates directly into improved retention. For the circular design the relationship inverts: its high-mass reinforced-concrete floor attracts a substantial embodied-carbon surcharge, so direct building cost rises faster than residual value and the ratio declines (from 53.7% to 50.4%), notwithstanding an increase in absolute residual value. The circular design is the only configuration in which the price instruments reduce value-retention efficiency, precisely because it alone carries sufficient embodied carbon for the surcharge to outweigh the residual value gain.

Table 7.12: Residual value as a share of direct building cost (RV/DB), before and after full effect of the price-based instruments, at base (DfD-0) and improved (DfD-1) detachability.

	DfD-0		DfD-1	
Structure	**Before**	**After**	**Before**	**After**
Wood structure	36.8%	38.9%	43.7%	45.5%
Steel structure	-28.8%	-12.1%	5.8%	15.4%
Traditional design	-26.2%	-8.9%	19.5%	22.6%
Circular design	53.7%	50.4%	56.6%	52.8%

The price-based instruments (labour tax reduction and carbon pricing) favour bio-based materials: the wood structure is already positive and improves further under the policy mix in both design scenarios (from 36.8% to 38.9% at base detachability, and from 43.7% to 45.5% at the improved level), reflecting its low embodied carbon and high recoverable material share. The regulatory instrument, by contrast, is what rescues the conventional, material-dominant structures: both are strongly negative at base detachability (steel -28.8%, traditional -26.2%) and turn positive only once detachability is improved (steel 5.8%, traditional 19.5%), so for these structures the detachability threshold does the decisive work rather than the price-based instruments.

The circular design structure, containing bio-based and detachable conventional materials, illustrates a mild tension rather than a conflict. It benefits most from the detachability threshold, but because it is material-dominant in absolute mass terms it is slightly disadvantaged by carbon pricing, with its RV/DB ratio easing from 53.7% to 50.4% at base detachability and from 56.6% to 52.8% at the improved level. This downward shift is however modest: the structure remains the strongest performer in every scenario, so the carbon surcharge tempers rather than undermines its value-retention efficiency (Table 7.12).

7.6. Results Expert Interviews: Model Assumptions and Validation

The section goes into the results of the expert elicitation, based on ten expert interviews. A more detailed overview of the expert interviews can be found in Appendix C, where data derived from the experts interviews were coded and processed according to the explanation in chapter 3.

*Quantitative insight*s (3.4.1) were derived during expert eliciation for model assumptions. Transmission logic, scenario plausibility and values were agreed upon and applied in the scenario model, however the labour tax reduction stays a relatively unknown policy instrument, whereas carbon pricing is more common, and usable input values were suggested and applied. Model assumptions were changed if values were indicated, such as the carbon pricing values of (PBL, 2021) or building products detachability index B.3. Furthermore, The assumption of zero revision costs (RC = 0%) was challenged in the current time of writing (June, 2026), but it was also argued this would improve overtime as reuse and the usage of bio-based materials become more standardised. Several experts emphasised that inspection, certification, and reprocessing activities generate high costs; this prompted the introduction of sensitivity ranges for revision-related parameters, after which experts were asked if 5% and 10% would be more reasonable in the current scenario. Experts also indicated that storage costs may be both underestimated and overestimated because actual storage durations often exceed the model assumption of six months.

This prompted the introduction of sensitivity ranges for storage-related parameters, with experts indicating that both longer storage durations (12 months) or scenarios without storage could be more representative. Experts noted the exclusion of inflation deemed the residual value as conservative. Experts raised comments regarding quality-reduction for steel, which is highly sensitive where and how building products are stored. The results illustrate steel is sensitive to quality reduction. Experts highlighted that embodied carbon (EC) values had to be incorporated in sensitivity analysis due to uncertainty.

Qualitative insights (3.4.1) were derived from expert interviews for model validation, to ensure the completeness of the model. The model completeness check revealed several insights. The interviews highlighted that the feasibility and impact of policy instruments depend strongly on wider institutional and market conditions, including certification practices, procurement routines, standardisation, storage capacity, and the development of secondary material markets. The low costs of new raw materials as well as labour-intensive activities such as disassembly, inspection, sorting, and remanufacturing were validated as key barriers to circular construction. Labour tax was assumed to have a stronger effect according to most experts, which adds to the modelled results. Two missing dimensions were mentioned particularly often: time dynamics, especially the mismatch between long- term circular value and short-term project costs, and market mechanisms related to supply–demand matching for recovered materials. The validation process therefore confirms the relevance of the selected incentives and residual value as analytical lens: expert interviews with public building commissioners validated a lower annual charge through circular depreciation, as a way of reallocating the freed room, toward maintenance and monitoring, so recognised material value can be tracked and claimed at end-of-life, or toward procuring and designing with more detachable and bio-based products The absence of empirical data due a lack of information on material passports and the low maturity of secondary-material markets was validated and highlighted.

7.7. Results Sensitivity Analysis

The core question of the sensitivity analysis is: *"Would my conclusion change if I had made different model assumptions?"* The analysis focuses on the steel structure and the CLT floor slab. Together these provide a meaningful contrast: a policy-sensitive conventional material with low detachability, and the highest-performing bio-based material, with the most favourable base values for material share and detachability (Chapter 6.5). Absolute value outcomes and input variables can be found in Appendix D.4.

A deterministic one-at-a-time (OAT) analysis is performed. Each input parameter is varied across while all others are held at their baseline, isolating individual contributions to residual value. The parameters fall into three groups: policy parameters, technical correction factors, and correction factor assumptions, which are tested alongside inflation as a macroeconomic driver. The tested ranges are not uniform across parameters: continuous variables such as material share, direct building cost, and the labour-tax wedge are varied by ±20%, whereas the correction factors move between discrete detachability and quality bands, and revision cost is stress-tested from zero. The rankings therefore reflect the influence of each parameter within its own plausible range. The residual value formulation itself does not include inflation: all base values in this thesis are expressed in present terms, which makes them deliberately conservative. To test inflation, residual value is compounded over the 24-year horizon (from 2026 to 2050), and the inflation *rate* is then varied around its central value of 3.3% derived from Centraal Bureau voor de Statistiek (2026).

Sensitivity Analysis CLT FLoor

The one-at-a-time (OAT) deterministic sensitivity analysis for the CLT floor ranks parameters by their change in residual value from baseline, as shown in Figure 7.13. Quality reduction shows the largest impact, followed by inflation; material-value parameters (material share, direct building cost, loss factor) occupy the mid-range, while detachability and price-based parameters (CO_2 price, embodied-carbon factor) sit at the bottom.

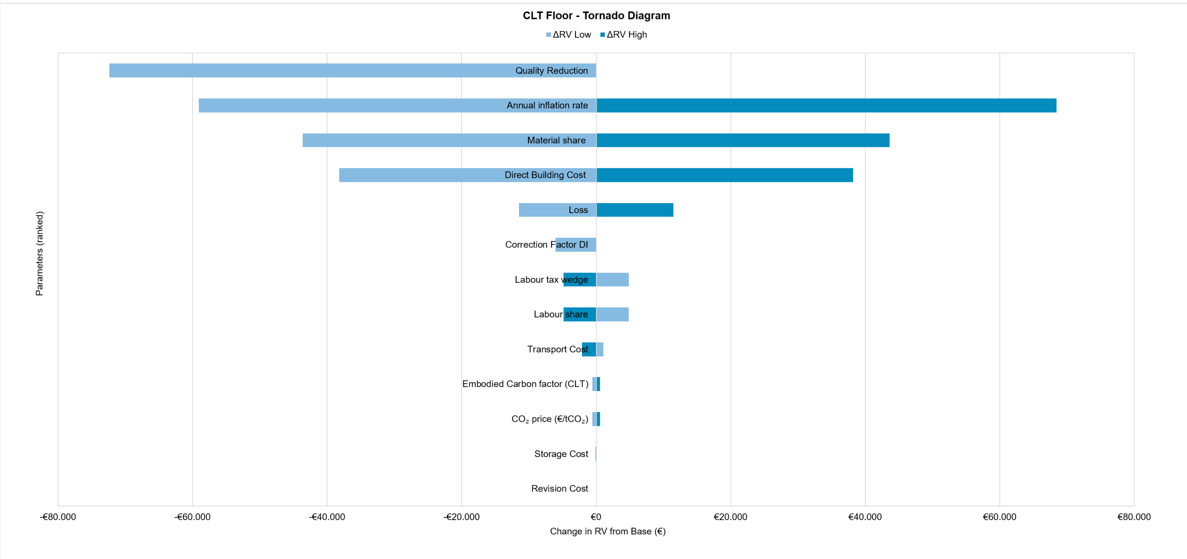

Figure 7.13: OAT sensitivity analysis CLT floor: parameters ranked by change in residual value from baseline.

In the model, quality reduction is fixed at zero in the baseline and can therefore only reduce residual value in a OAT sensitivity analysis. Its position at the top of the ranking reflects uncertainty, where the impact is strong if CLT floor loses its assumed quality-retention advantage, which in practice could be caused by less favourable storage or ageing conditions. Revision cost, shows no effect at all, but this is an artefact of the one-at-a-time analysis; with quality held at zero in the baseline, varying it alone leaves residual value unchanged. Its influence would surface only in combination with quality degradation. Setting inflation aside as a macroeconomic driver, the parameters that move residual value most are those that determine material value: material share, direct building cost, and the loss factor. The detachability-related parameters are comparatively minor, because the CLT floor already sits well above the detachability gate, so improving detachability adds little to a product that is already recoverable. The price-based parameters, the CO_2 price and the embodied-carbon factor, sit at the bottom of the ranking.

Sensitivity Analysis Steel Structure

The OAT deterministic sensitivity analysis for the steel structure indicates that material loss and the detachability correction factor (corDI) exert the largest sensitivity on residual value, followed by quality reduction and inflation, as shown in Figure 7.14.

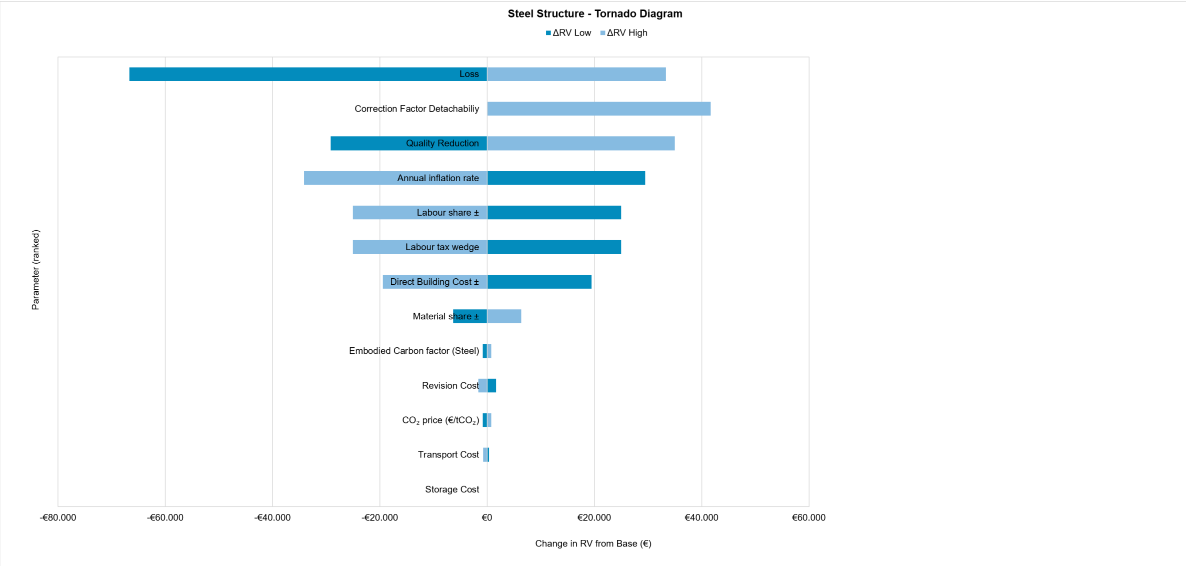

Figure 7.14: OAT sensitivity analysis steel structure: parameters ranked by change in residual value from baseline.

Material loss and corDI are both governed directly by the detachability index (DI), and their dominant position in the ranking reflects the model's sensitivity to detachability performance for conventional materials. Quality reduction and inflation show a notable but smaller effect, indicating that degradation processes also contribute to variation in residual value, though to a lesser extent than the detachability-related correction factors. This connects to the exposure of structural steel to corrosion and adverse storage conditions, which experts in Section 7.6 identified as a particular source of uncertainty for steel.

Conclusion Sensitivity Analysis

Across both materials, the parameters that drive residual value sensitivity are detachability- and quality-related, but which of the two dominates is conditional on where each material sits relative to the detachability gate: CLT, is primarily exposed to quality-degradation risk, while steel, sitting below it (DI 0.27), is primarily exposed to detachability performance. This divergence carries an important interpretive point that confirms the result of Section 7.2: steel is not a write-off material. Its negative residual value arises from low detachability, which drives both the material loss and the disassembly cost that dominate its sensitivity. What damages material value in the steel structure is not the material itself but the way it is designed. Inflation is influential in both cases but does not dominate either ranking, and its exclusion from the base formulation can be interpreted as a conservative modelling choice. The sensitivity analysis reinforces the results of the scenario analysis, price-based instruments act on residual value, but technical parameters and the design on which they governs how much variation is possible. Limitations of the OAT design should be considered. The tested ranges are not uniform across parameters: continuous variables such as material share, direct building cost, and the labour tax are varied by ±20%, correction factors move between discrete detachability and quality bands, and revision cost is stress-tested from zero. The resulting rankings therefore reflect each parameter's influence within its own plausible range, not a standardised elasticity measure, and cross-parameter magnitude comparisons should be read accordingly. Second, OAT varies one parameter at a time and cannot detect interaction effects, shown by revision cost's artefactual null result, which is conditional on quality being held at its baseline of zero. The model's apparent robustness to price-based and detachability assumptions for CLT, and to quality assumptions for steel, should therefore be read as evidence of low sensitivity within the tested one-way space, rather than as a guarantee that no joint parameter effects exist.

7.8. Conclusion Phase II: Policy Mix Analysis

Having assessed the policy instruments individually, relatively and in combination, the final step evaluates the policy mix as a whole. The policy-mix literature offers four criteria for this — consistency, coherence, credibility, and comprehensiveness (Mavrot et al., 2019; Rogge & Reichardt, 2016) — each drawing on a different part of the evidence: the modelled interaction effects for consistency, the governance landscape for coherence, the expert elicitation for credibility, and the barrier diagnosis for comprehensiveness.

Consistency

Consistency concerns the alignment of the policy mix's elements, ranging from the absence of contradictions to the presence of synergies between instruments (Rogge & Reichardt, 2016). By the directional test, the mix is consistent: every instrument raises residual value in all four configurations, and none reduces it. Interaction between the price-based instruments is positive but negligible: between €162 and €1,735 at base detachability and up to €8,347 under improved detachability, in every case no more than 3.4 percent of the combined effect (Tables 7.5 and 7.11). Labour tax and carbon pricing therefore act near additively rather than synergistically, which by Rogge and Reichardt (2016) marks weak rather than strong consistency: the instruments do not undermine one another, but neither do they generate significant positive interaction. One case moves against the others on the relative residual value measure: the Case Study 2 circular design rises in absolute residual value yet sees its residual value to investment ratio (RV/DB) fall (Table 7.12). This is the only structural configuration in which the price-based instruments raise absolute residual value while simultaneously lowering value-retention efficiency: residual value increases, but direct building cost rises faster, so the value retained per euro invested declines.

Coherence

Coherence concerns whether the policy-making and implementation processes behind the mix are systematic and mutually supportive (Rogge & Reichardt, 2016). Coherence is limited by institutional separation: the three instruments are made and implemented through different processes at different governance levels. The labour tax reduction requires national fiscal reform, carbon pricing builds on the existing European and Dutch ETS and carbon pricing trajectories, and the detachability threshold could be implemented through municipal procurement standards or a future (European) standard. Because these processes are not coordinated through any shared planning or implementation structure, the mix exhibits weak implementation coherence, even though the instruments are directionally aligned in their effect on residual value. The residual value methodology provides a conceptual rather than an institutional link. The policy instruments are not jointly governed and operate through separate fiscal and regulatory channels, so their coherence is analytical rather than institutional. Each targets the barriers to circular construction and raises residual value, so the mix is mutually supportive in its effect. It is not systematic, however: the instruments act in sequence, as the detachability threshold sets the base on which the price-based instruments then act.The mix is thus coherent in direction, but not necessarily in process.

Credibility

Credibility concerns the extent to which the mix is believable and reliable over time (Rogge & Reichardt, 2016), which is assessed here through expert elicitation. Experts agreed on the transmission mechanisms and scenario plausibility reflected in the model design, and the relative ordering of effects, the labour tax reduction stronger than carbon pricing, aligned with their expectations. The instruments were not received as equally credible, however. Carbon pricing raised no substantial concerns, consistent with its established European and Dutch trajectory. The labour tax reduction was seen as more uncertain and politically more radical, given its dependence on national fiscal reform. The detachability threshold was supported in both its importance and its feasibility, regarded as an instrument that can realistically be achieved through procurement or standardisation. Experts also flagged assumptions such as revision costs, the six-month storage duration, and the exclusion of inflation; these affect absolute outcomes but not the relative ranking, and excluding inflation is a conservative choice that bounds rather than weakens the results. The sensitivity analysis confirms that the remaining uncertainty is driven mainly by technical parameters: detachability-related correction factors and quality for the steel structure, and quality reduction together with the material-value parameters for the CLT floor. Credibility therefore rests more on the technical assumptions derived from the database than on the policy parameterisation, within the bounds of the ten expert interviews. Over time, standardisation could play a role: if detachability becomes an established design norm rather than a barrier, the assumptions that currently introduce uncertainty, such as revision costs, would themselves become more reliable.

Comprehensiveness

Comprehensiveness concerns how extensively the mix addresses the relevant market, system, and institutional failures (Rogge & Reichardt, 2016); this analysis focuses on the economic and governmental dimensions. Each diagnosed barrier maps to one instrument: carbon pricing for the under-pricing of virgin materials, labour tax reduction for the cost of labour-intensive circular work, and the detachability threshold for weak recognition of recoverability. Within that scope the mix is comprehensive, each barrier mapping to a suitable instrument and each instrument to a model parameter, while the remaining barriers, recognising end-of-life value and fiscal mechanisms, are absorbed into the evaluative lens of residual value. Expert elicitation surfaced barriers beyond this scope, such as the absence of material-passport data for Dutch public buildings, immature secondary-material markets, the mismatch between long-term value and short-term budgets, and supply–demand matching for recovered materials, which sit in a broader societal and institutional context of circular construction.

Conclusion Policy Mix Criteria

Across the four criteria, the mix consistently increases residual value without conflict between instruments, though the price-based instruments interact near-additively rather than synergistically, and one configuration (Case Study 2 - circular design) shows absolute residual value rising while value-retention efficiency (RV/DB) falls. Coherence holds in direction but not necessarily in policy-making and implementation process: national, European, and municipal governance levels means their alignment is analytical rather than institutionally coordinated, which has implications for how the policies would be implemented. Credibility rests more on technical parameter assumptions drawn from the database than on the policy parameterisation itself, within the scope of the ten expert interviews and sensitivity analysis. Comprehensiveness holds within the economic and governmental dimensions targeted by the three instruments, but expert elicitation surfaced barriers such as material-passport data gaps, immature secondary-material markets, and short-term budget cycles, that remain open questions beyond this study's scope. Together, these results suggest that residual value can strengthen the economic viability of bio-based and detachable materials, and that the three instruments operate coherently within the residual value methodology used for circular depreciation of Dutch public buildings.

8 Discussion

This chapter synthesises and interprets the findings. The analysis builds on the results presented in Chapter 7 and the expert elicitation (Appendix C), and situates them within the theory of circular construction. Section 8.3 discusses the limitations of the research, followed by a reflection on the methodological approach in Section 8.4. Section 8.5 outlines the implications for policy, design, and theory, while Section 8.6 assesses the robustness and generalisability of the findings. Finally, Section 8.7 recommends future research directions.

8.1. Interpretation of the Findings

The aim of this research is to analyse how selected policy instruments can incentivise circular construction of Dutch public buildings, by quantifying their effects on the residual reuse value of building products. The central finding is that policy instruments and design characteristics affect different parts of residual value. Price-based instruments, such as labour tax reduction and carbon pricing, influence the *level* of residual value by changing the costs of material production, recovery, and reuse. Detachability, by contrast, determines whether residual value can be realised at all. This mechanism operates through the depreciation base. Recognising residual value raises the floor to which a public asset depreciates, reducing the depreciable amount. Expert interviews suggest municipalities do not necessarily lower annual capital charges (*kapitaallasten*), but instead reallocate the freed space toward maintenance, monitoring, or circular procurement and design. In this way, material value can be tracked and potentially realised at end-of-life. The residual value methodology and the selected policy instruments tend to favour low-mass, detachable materials, which is consistent with circular construction objectives in the Netherlands, such as Dutch circularity criteria from Het Nieuwe Normaal (2024). In the 'circular design' of Case Study 2 ('School'), due to high direct building costs, material mass and carbon intensity, a modest reduction occurs in the residual value-to-investment ratio due to the carbon pricing. However, this reduction remains limited, and the circular configuration still performs strongest across all scenarios. Carbon pricing therefore moderates rather than undermines economic value retention, while reinforcing the broader sustainability signal. Within the scope of this research, the instruments do not conflict with the residual value methodology, but reinforce its logic. Circular configurations, combining bio-based and detachable conventional materials, consistently achieve the highest residual values. This suggests that, under the conditions modelled, circular construction and sustainability objectives are not necessarily in trade-off, but can be aligned. The findings suggest that financial residual value can reshape the cost structure of circular construction without redefining its underlying principles. It supports circular choices by strengthening the position of bio-based materials and by making it more worthwhile to design conventional materials, such as steel and concrete, for disassembly.

8.2. Confrontation and Contribution to Theory and Literature

The findings can be situated within the multidimensional definition of circular construction adopted in this thesis, following Ossio et al. (2023), in which value retention is enabled by technology, management, government policy, business models, and stakeholder behaviour. While this framework emphasises the dynamic and multidimensional nature of circularity, the present study engages these dimensions unevenly. It operates most directly within the domains of *government policy* and *business models and management*. In doing so, the thesis reframes circular construction more explicitly as a question of depreciation, valuation, and accounting. The research findings and research positioning introduce a degree of tension with circular construction theory and literature. Circular construction is commonly approached as a multidimensional concept spanning technological, environmental, societal, behavioural, and economic domains (Pomponi & Moncaster, 2017).

This analytical focus on the economic and governmental dimensions is deliberate, however, environmental and social value dimensions remain only partially addressed, despite their central role in circular construction frameworks (Ossio et al., 2023; Pomponi & Moncaster, 2017). Environmental value is incorporated through LCA data of case studies and embodied carbon data (van Oostveen, 2026; WSP Nederland B.V., 2023), but factors such as carbon storage in bio-based materials are less developed. Social value is addressed only indirectly, through labour taxation, and receives no explicit analytical focus in the model. One expert raised the example of a project where the labour-intensive activities of circular construction, such as disassembly and sorting, were carried out by workers at a distance from the labour market. The same instrument that raises residual value can therefore also generate social return. The model, however, captures only the financial effect and leaves this wider social value outside its scope. This does not invalidate these dimensions, but it does limit the scope of the findings within circular construction theory. The results do not represent circularity in a comprehensive sense, but rather those aspects that become visible within economic and governmental frameworks. This premise is supported by analyses that emphasise the need for stronger business cases and financial incentives for circular construction (Rijksoverheid, 2023; WKR, 2026). The findings are consistent with this framing, but do not in themselves establish circular construction of Dutch public buildings. This creates a conceptual tension: while material value visibility and economic viability may be necessary to influence decision-making, it may also underrepresent dimensions of value that cannot be easily monetised.

A related confrontation with academic literature concerns the role of stakeholder behaviour. Kirchherr et al. (2018) identify cultural factors, such as limited awareness and hesitant adoption, as among the most persistent challenges to circular construction. The findings of this thesis do not resolve this tension, but suggest a more conditional interpretation. Financial residual value and the examined policy instruments can change the conditions under which decisions are made, but whether this translates into behavioural change remains uncertain within the scope of this research. From this perspective, residual value is not a complete solution, but a stepping stone: a value that is not recognised financially is unlikely to be considered in practice.

A further point concerns the temporal mismatch identified in the literature. Calisto Friant et al. (2021) argue that where price signals favour linear models, circular options remain niche, and decisions are governed by the iron triangle of time, scope, and budget (Kooter et al., 2021). Similarly, van Stijn et al. (2023) identify additional time, labour, and costs associated with circular design as key barriers. While this is empirically supported, it also points to a tension in how these factors are interpreted. The additional design time required for circular construction is not merely a cost, but a condition for technical feasibility, particularly for strategies such as design for disassembly. The findings suggest that the issue may not lie in the presence of additional time and cost itself, but in how their benefits are accounted for. Residual value is realised only at the end of a building's life cycle, often several decades in the future (Brand, 1995). Within short-term budget horizons, material value carries limited weight in present-day decision-making. As a result, time invested in circular design appears as an immediate cost, while its benefits remain distant and uncertain. From this perspective, circular depreciation becomes a critical mechanism. By translating future residual value into a present, annualised balance-sheet effect, it shifts part of the value of circular design forward in time. This does not remove the time constraint identified in the literature, but may change how it is evaluated. The contribution of this thesis is therefore not to challenge the existence of time-related barriers, but to show that their impact is partly a function of how value is temporally represented.

This section concludes by identifying the clearest contribution of the thesis to the literature on *enablers*. Circular construction literature has predominantly focused on barriers (van Stijn et al., 2023), while enablers remain less developed. This thesis contributes by specifying the financial-economic and governmental conditions under which residual value can be recognised and recovered, and by linking policy instruments directly to these conditions. price-based instruments address under-priced virgin materials and labour-intensive recovery (Azcarate-Aguerre et al., 2022; Mhatre et al., 2020; Munaro & Tavares, 2023), while the detachability requirement responds to the absence of design-for-disassembly incentives (Allam & Nik-Bakht, 2023; Tirado et al., 2022). Finally, the thesis shows circular construction may be technically feasible, but without financial visibility, they are unlikely to become economically competitive in decision-making contexts. Within this framing, residual value occupies a specific and bounded role: following Jiang et al. (2022), residual value is treated as a prerequisite of circularity, not a measure of it. The contribution of the thesis is therefore deliberately confined to making one previously less visible dimension more visible and quantified, recognising that this does not capture circular construction in its full sense.

8.3. Research Limitations

The design and data limitations of the methodological design are set out in Section 3.6; this section concerns the limitations that bound the *findings* of this research.

Limitations in Data and Analysis The empirical basis is limited in three places, all reflecting how new this topic is in practice. First, no empirical project-level data on the residual value of disassembled buildings was available, the technical parameters or value of recovered materials therefore rely on theoretical calculations. Second, the case studies rely on external sources, with building-product data mapped onto four structural configurations under transparent but unverified assumptions rather than empirical observation. Third, the labour tax trajectory is itself under-researched: no usable scenario data were identified beyond the (Copper8, 2022) project, though the reduction rates were not contested during expert elicitation. A consequence of limited data concerns the sensitivity analysis, which uses a deterministic one-at-a-time (OAT) sensitivity analysis, which isolates each parameter's individual influence but cannot capture interaction effects or joint uncertainty. Capturing interaction effects and joint uncertainty would require a variance-based approach, which was not pursued: the residual-value methodology is recent and rests on a thin empirical base. The deterministic results are therefore best read as indicative of relative sensitivity rather than as probabilistic estimates, with rankings reflecting each parameter's influence within its own plausible range.

Research Scope. The scope is bounded to the load-bearing structure: beams, columns, and floor slabs. The focus the structural layer of a building combines high material mass, cost significance, and embodied-carbon relevance (D'Amico & Pomponi, 2020). Foundations, basements, walls, and other building layers were excluded for analytical clarity and comparability. This keeps the analysis tractable but narrows the generalisation of the findings, and the long lifespan of structural systems (fifty years and more (Brand, 1995) means the analysis necessarily reasons about future value retention under substantial uncertainty. Building products with shorter lifespans may provide empirical data sooner and offer an earlier testing ground for the approach. The scope also filters out other circular strategies, such as refuse, renovation, and recycling. Several experts stressed high-quality recycling, particularly for concrete, while others noted that avoiding new construction altogether is sometimes the most circular option. Experts pointed to aluminium, copper, and glass as the most promising candidates for extending the material scope.

A further consideration concerns the fiscal scope of the two price-based instruments. Consistent with the building-level unit of analysis, the model evaluates how each instrument affects residual value at the level of a building, not its wider effect on public revenue. This matters for interpreting what the input trajectories represent: PBL's *effective* CO_2 price expresses the societal cost of reducing emissions to the target efficiently under a given WLO scenario rather than a charge levied on embodied material, while the labour rate of Copper8 (2022) reflects the employer's tax burden within a revenue-neutral shift, in which a lower labour tax is financed by heavier taxation of resource use and pollution. The model applies each instrument separately and is not intended as a net fiscal assessment. The results are therefore best read as each instrument's effect on residual value at the building level, which is the scale at which the residual-value methodology operates.

8.4. Reflection on Research Approach

First, it's important to recognise a quantitative, ex-ante evaluation can give the impression of neutrality, as though it only reports what the instruments do to a number. The thesis rests on the position that the linear default, where a public asset is depreciated to zero and its material value disregarded, is unsustainable and misaligned with current governmental circular economy goals. Making residual value the central evaluative lens is itself a normative choice. It is a bounded one. The analysis does not hold that every circular option is automatically desirable, nor that higher residual value should override other public considerations of social or environmental value.The main ethical risk that follows is over-financialisation. Expressing circularity through a single monetary quantity could be read as reducing a multidimensional objective, as defined by (Ossio et al., 2023), to what fits in a euro figure, and underplaying the social and environmental dimensions the formula does not capture. The research approach is intended to strengthen the economic viability for bio-based and detachable materials that also serve environmental and social goals, leaving those dimensions to be assessed in their own terms. The thesis mitigates this by treating residual value as a prerequisite of circularity rather than a measure of it, following Jiang et al. (2022).

Three research frameworks condition the findings. First, the ex-ante design suits instruments not yet implemented in the form modelled and makes its assumptions transparent, but cannot capture how policies are negotiated or adapted in practice, a gap expert elicitation mitigates but does not resolve. Second, the top-down economic and governmental perspective aligns the analysis with its intended audience of ministries and public building commissioners, securing policy relevance, but treats bottom-up dynamics such as contractor and on-site practice indirectly. Third, the Policy Compass embodies a specifically Dutch conception of policy design, which may bias the analysis toward instruments that fit institutional logics. Aligning with the Compass strengthens relevance for the Dutch context but may narrow the instruments considered, leaving more interventionist options underexplored. The same applies to residual value itself, which is not yet an internationally established valuation concept, so the framing remains bound to the Dutch public buildings context. These choices delimit the findings rather than diminish them: each was adopted to keep the analysis explicit, policy-relevant, and tractable.

8.5. Implications

The findings have several implications for both practice and research:

Practical implications The thesis suggests implications for national policy makers, public building commissioners, and other circular construction actors. The main implication for stakeholders, following Peng and Cao (2025), is the importance of recognising material value at every stage of a building product's life. Design, procurement, use, and end-of-life are best understood as an interconnected chain. Within this chain, financial residual value supports decision-making by making future material value visible earlier in the process, strengthening the economic viability of detachable and bio-based materials.

For *public building commissioners*, a key implication is that material value retention cannot be realised at end-of-life unless it is embedded at the design stage. The recoverability that policy instruments aim to incentivise is determined upfront through material selection and design for disassembly. Policy instruments can influence circular construction costs and material value recognition, but operate after the design decisions that determine recoverable value have already been made.

For *policymakers*, the main implication is that the three instruments differ not only in effect, but in feasibility and institutional requirements. A labour tax reduction has the strongest effect within the model but entails significant fiscal and political trade-offs, as it requires redistribution within the broader tax system. Carbon pricing is more aligned with existing policy trajectories, but its effect on residual value is more modest under the conditions analysed. Its main relevance lies in reinforcing price signals without undermining the residual value mechanism. The detachability threshold appears the most directly actionable, as it can be implemented through procurement and design requirements, although its effectiveness depends on technical standardisation and sector readiness. The broader reading is that these policy instruments are best understood as incentives that redirect material selection and design towards circular construction.

Scientific implications The research started from an identified research and policy gap: current research insufficiently links circular construction principles to financial valuation frameworks, limiting their integration into investment decisions. In the wider debate, research and policy have predominantly concentrated on *operational* energy efficiency, while material efficiency has received comparatively little attention (Allwood et al., 2011; Pomponi & Moncaster, 2016, 2018). The findings of this thesis align with the call for that shift. This thesis responds by repositioning residual reuse value from an accounting output to an analytical mechanism that links policy design, procurement logic, production and design, and material choice. The thesis conceptualises residual value not as an accounting outcome, but as something policy can act on: a way for financial incentives and design choices to shape how much economic value a building's materials retain at end-of-life. This shows how policy can guide material choices and value retention across the building's life, complementing the carbon and energy concerns that dominate the use phase with attention to the value held in materials at end-of-life.

Methodologically, few studies connect policy design to financial outcomes at the building level through scenario-based modelling. This thesis contributes an ex-ante evaluation design that combines academic barrier analysis, policy-document analysis, expert elicitation, scenario modelling, case-study application, and sensitivity analysis; its strength lies not in eliminating uncertainty but in making it explicit and analytically tractable, through proxy documentation, elicited parameter ranges, and sensitivity analysis. The resulting structure is transferable, diagnosing barriers and enablers, mapping instruments onto a value formula, modelling their interaction, evaluating the mix, and expert validation, where it could be applied to other materials, building layers, or value-retention questions beyond the scope studied here.

Empirically, the thesis provides, to the author's knowledge, the first Dutch assessment of how policy affects the residual reuse value of structural building materials in public buildings. This empirical contribution remains bounded: the findings are most credible within the chosen material scope, the model assumptions, and the Dutch public-sector context, and should be read as analytically grounded rather than universally generalisable.

8.6. Robustness, Validity, and Generalisability

The robustness of these findings rests on a mixed-method design combining literature and policy document analysis, scenario and sensitivity analysis, and expert elicitation. Because these methods converge on the same conclusions, the central findings can be held with greater confidence. *Robustness* is real but bounded. Validation on ten interviews establishes plausibility but not empirical proof. The findings are therefore most reliable when used for comparison and direction, and weakest when read as exact values tied to a specific point in time. This limitation does not undermine the core conclusion: residual value is governed primarily by design and material characteristics, and only secondarily by price-based instruments. In general, the *validity* of the work rests less on statistical representativeness, which an ex-ante scenario model of two case studies cannot claim, than on the explicitness of the research logic. Triangulation across multiple methods, data sources, and theories, together with the visibility and documentation of its assumptions, contributes most to the validity of the findings. *Generalisation* should be understood in analytical rather than statistical terms. The study does not aim to produce universally generalisable numerical outcomes; instead, it demonstrates a method that can be analytically reproduced and transferred to other building materials, building layers, and value-retention questions. While the specific results remain bounded to the chosen research boundaries and the Dutch public sector context, the methodological approach can be applied to other materials within the construction sector and, potentially, extended to other sectors that depend on linear economic systems and virgin material use.

8.7. Future Research Directions

The limitations and reflections above point to several directions for further research. It is worth noting that there remains considerable room for it: the residual value of building products in circular construction is still a relatively unexplored topic, with limited academic research both in the Netherlands and abroad (Jiang et al., 2022).

The first direction concerns the step toward richer empirical data. Dedicated empirical data on the value of recovered materials is the single most valuable extension of this work. Within the adapted methodology, the correction factors embedded in the residual value formula would benefit from project-specific empirical data. As an illustration, the findings of the thesis suggests that the room freed within the annual capital charges by recognising residual value, may be reallocated toward monitoring and maintenance. Yet, the model treats quality reduction as exogenous. If that reallocated maintenance in fact slows degradation, it would lower quality reduction and so raise residual value, closing a feedback loop the present methodology leaves open. Testing whether circular depreciation, through the maintenance it funds, measurably improves material-quality retention over time would connect the fiscal mechanism directly to one of the model's most influential parameters.

The second direction is to complement the top-down economic and governmental framing with bottom-up research grounded in on-site practice: how buildings are actually taken apart at end-of-life, how demolition and disassembly are carried out on site, and how stakeholder behaviour determines whether residual value is realised in the field rather than only on paper. The present framing is strongest on how institutional conditions might be reconfigured and weaker on what happens on the ground during demolition; bottom-up research into on-site practice would address that gap.

The third direction is to broaden the material and building-layer scope beyond the structural layer of public buildings, to services, facades, and other shearing layers, and to scarce materials such as aluminium, copper, and glass. This would test whether the result holds outside the structural frame and how far the findings generalise, and give more options for empirical data availability.

The fourth direction is methodological. The single-dimension financial lens could be complemented by methods that capture the environmental and social dimensions the present model brackets out, for example life-cycle assessment or cost–benefit analysis, so that circular value is assessed across more than its economic dimension alone. The LCA data for Case Study 1 are already available in the WSP Nederland B.V. (2023) environmental assessment, providing a concrete starting point for such an integration.

9 Conclusion and Recommendations

This chapter presents the main findings of the study and their implications for the role of financial incentives in circular construction. It first answers the sub-questions (Section 9.1), then the main research question (Section 9.2), and concludes with recommendations derived from these findings (Section 9.3).

9.1. Answers to the Sub-Questions

Sub-Question 1

What economic and governmental barriers and enablers to circular construction are identified in academic literature?

The literature review identified economic and governmental barriers as the two most frequently reported categories. Three main economic barriers are identified: the structural under-pricing of virgin materials, the high cost of labour-intensive circular activities such as disassembly and remanufacturing, and the invisibility of residual value in prevailing valuation frameworks. The main governmental barriers identified are the absence of a binding requirement or strong incentive for design for disassembly, and fiscal distortions combined with weak public financial support. The decisive enabling insight is that these barriers are not fixed structural conditions but institutional design choices that can be reconfigured into enabling conditions through targeted policy.

Sub-Question 2

What economic and governmental mechanisms produce the 'linear default' for Dutch public buildings?

The analysis of three Dutch policy documents extends the findings of the literature review and of Sub-Question 1. The main finding is that the linear default is reproduced not because policy instruments are absent, but because existing instruments are calibrated to limit linear harm rather than to reward circular value. All three sources converge on the diagnosis that circular construction is structurally more expensive than linear construction, driven by cheaper virgin materials and higher labour and process costs. Two mechanisms illustrate the findings. First, the MKI methodology can, in certain configurations, penalise higher-value recovery, working against the circular outcome it is meant to steer towards. Second, the MPG requirement operates as a ceiling that caps linear impact above a threshold but offers no reward for circular performance below it, so a building that banks recoverable material value gains no advantage over one performing at the permitted maximum. In both cases a similar pattern occurs: the instruments limit linear harm but do not reward circular value, leaving the value created through circular construction invisible.

Sub-Question 3

Which policy instruments are most suitable for incentivising residual reuse value, given the identified barriers and the variables of theoretical residual value?

Suitability was defined twofold: each instrument had to respond to a diagnosed barrier to circular construction and correspond to a policy-sensitive variable in the residual value methodology, so it could be operationalised within the model. On this basis, three instruments were selected. A labour tax reduction (price-based) addresses the cost of labour-intensive circular activities and acts on the labour and material cost shares. Carbon pricing (price-based) addresses the under-pricing of virgin materials and acts on the material-value base through an embodied-carbon surcharge on the direct building costs. A detachability threshold (regulatory) addresses the absence of a binding design-for-disassembly requirement and acts on the detachability index. The analysis proceeds not to select a single optimal instrument, but to analyse a policy mix of price-based and regulatory instruments acting at different stages of a building product's life, to redirect materials away from linear end-of-life pathways. Each instrument influences residual value through a distinct but related mechanism. A reduction in labour tax lowers the relative share of labour costs within direct building costs, which raises the proportional share of material value while simultaneously lowering detachment-related costs; together these raise residual value. Carbon pricing on virgin materials introduces an embodied-carbon surcharge that most affects materials with high mass and carbon intensity, raising the material-value base and thereby residual value. A detachability threshold, based on design for disassembly, improves how easily materials can be recovered, reducing both expected recovery losses and detachment costs; this raises residual value and can shift a building product from a 'write off' residual value value towards a positive residual value.

Sub-Question 4

To what extent do price-based instruments (a labour tax reduction and carbon pricing) and the regulatory instrument (a detachability threshold) affect residual reuse value, individually, relative to one another, and in combination?

The instruments act on different parts of residual value. The price-based instruments change the *level* of residual value, while the detachability threshold determines whether residual value can be realised *at all*. At base detachability, the labour tax reduction is the stronger and more consistent price lever compared to carbon pricing. The detachability threshold produces categorical shifts: it moves the conventional, material-dominant structures (a steel structure and a traditional design) from write-off to recoverable asset, while having a less significant effect on the bio-based dominant and already-detachable structures that sit above the detachability gate. Improved detachability strengthens carbon pricing as a policy instrument, because once materials are technically recoverable, embodied-carbon surcharges translate more strongly into residual value gains. When high buildings costs, material mass, and embodied-carbon intensity, and sufficient detachability coincide, carbon pricing can become the more dominant price-based instrument. Furtermore, the interaction between the two price-based instruments is positive but negligible, under two to three percent of the combined effect, so they act additively rather than synergistically.

Residual value expressed relative to investment shows the price-based instruments favour bio-based and detachable materials. The wood structure is already positive on value-retention efficiency and improves further under the policy mix in both design scenarios (from 36.8% to 38.9% at base detachability, and from 43.7% to 45.5% at the improved level), reflecting its low embodied carbon and high recoverable material share. The regulatory instrument, by contrast, is what rescues the conventional, material-dominant structures: both are strongly negative at base detachability (steel -28.8%, traditional -26.2%) and turn positive only once detachability is improved (steel 5.8%, traditional 19.5%), so for these structures the detachability threshold does the decisive work rather than the price signals. The circular design, combining conventional detachable and bio-based dominant materials, shows a mild tension rather than a conflict: it is slightly disadvantaged by carbon pricing, with its RV/DB ratio easing from 53.7% to 50.4% at base detachability and from 56.6% to 52.8% at the improved level. This downward shift is modest and not disruptive, since the structure remains the strongest performer in every scenario.

9.2. Answer to the Main Research Question

To what extent, and through which mechanisms, do policy instruments affect the residual reuse value of Dutch public buildings, and how can this incentivise circular construction?

Policy instruments can increase residual reuse value of structural building materials, but they do so unevenly, and only under particular material and design conditions. The price-based instruments raise residual value but cannot move it from a 'write-off' to recoverable asset, where the regulatory detachability threshold changes whether residual value can be realised at all. Detachability not only raises residual value directly; it also strengthens the price-based instruments, because once materials can be recovered, embodied-carbon surcharges and lower detachment costs feed more strongly into residual value. The decisions that create recoverable value are made at the design stage, which is where current Dutch circular policy has the least grip. Once residual value is recognised in the depreciation base it becomes a fiscal instrument in its own right, and not only a way of measuring value. The mechanism pulls in two directions: it favours bio-based materials, whose low embodied carbon and high recoverable share place them well under the price-based instruments, and it makes designing conventional materials such as steel and concrete for disassembly worthwhile. Recognising residual value raises the floor to which a public asset is depreciated, and expert interview findings indicate municipalities tend not to treat this as a lower annual charge, but as freed room within a constant *capital charges* line, which they reallocate toward monitoring, maintenance, or more circular procurement. Circular depreciation, read this way, does not change how much a municipality spends, but how that spending can be used for circular construction of public buildings.

9.3. Recommendations

The findings support recommendations of a conditional but actionable kind. The recommendations concern both the conditions under which residual value could become a more reliable basis for Dutch policy and the steps that can already be taken to recognise it.

First, build empirical evidence. Data on material passports for Dutch public buildings, and on the value of reused materials at the point of reuse, remain scarce. This includes the values underlying the methodology itself: empirical data on what secondhand materials and products are worth at larger scale, across multiple material types, is still limited. Improved data in these areas would strengthen the robustness of the theoretical residual value estimates adapted. At the same time, future market value is inherently uncertain, shaped by material scarcity and resource access, so residual value is best treated as a structured way of reasoning about retained value rather than a precise figure. Reliable gains lie in empirical data on the factors that determine residual value.

Second, include residual value in the financial decision-making for new public buildings. Residual value accounts for material value retention and supports the economic viability of detachable and bio-based materials. By making retained value explicit, it enables more balanced comparisons between circular and conventional materials in Dutch public buildings. Its main contribution is to make value retention visible across the building life cycle, which strengthens the case for investment in bio-based materials and design for disassembly, while complementing the use phase through the monitoring and maintenance that sustain material value over time. For *public building commissioners*, residual value can serve as a practical tool, incorporated directly into investment and design decisions for new buildings. It does not resolve circular construction barriers on its own, but it supports more balanced decision-making by making future material value easier to recognise and account for. For *policymakers*, residual value serves a different function, less as a tool than as a diagnostic, revealing where policy instruments such as labour tax reduction, carbon pricing and a detachability threshold could intervene. Within a sector marked by high environmental impact and accelerating resource depletion, making end-of-life material value visible through residual value may be a necessary step toward aligning financial decision-making with circular construction goals in the Netherlands, indicating where policy can act on the circular construction barriers and turn them into enablers.

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During the preparation of this thesis, the author used Microsoft Copilot to assist with language refinement, and to support code debugging in Excel. AI tools were used to improve the clarity of the written text and to identify and resolve errors in the code. No AI tool was used to generate interpretations, analytical content, research findings, or conclusions of the research. All AI-assisted outputs were carefully reviewed and edited by the author, who takes full responsibility for the content of this thesis.

A

Residual Value Methodology

A.1. Residual Value Calculations

This subsection sets out the residual value calculations. The methodology decomposes residual value into a recoverable material base from which a series of correction factors are subtracted. The residual value model decomposes direct building costs into material and labour components and accounts for losses, quality reductions, and recovery related costs. Source: Alba Concepts et al. (2025)

A.1.1. Calculations Residual Value Methodology

$$MaterialValue = DB \cdot \%\text{material} \tag{A.1}$$

where:

- DB: direct building costs (€)
- $\%$material: share of direct building costs attributable to materials
- $MaterialValue$ (Vmat): monetary value of materials before applying recovery-related reductions

From this material base, value reductions are applied to account for physical and quality related losses:

$$Loss = MaterialValue \cdot \%\text{loss} \tag{A.2}$$

where:

- $Loss$ (L): value lost due to material damage during disassembly (€)
- $\%$loss: proportion of material value lost, dependent on the detachability index (DI)

$$QualityReduction = MaterialValue \cdot \%\text{quality} \tag{A.3}$$

where:

- $QualityReduction$ (QR): reduction in value due to ageing and technical condition (€)
- $\%$quality: proportion of value reduction based on condition score (NEN 2767)

$$RevisionCosts = QualityReduction \cdot \%\text{revision} \tag{A.4}$$

where:

- $RevisionCosts$ (RC): additional costs required to restore or examine usability (€)
- $\%$revision: share of quality reduction requiring revision or certification

$$LabourCosts(Clab) = DB \cdot \%\text{labour} \tag{A.5}$$

Consistent with the Excel implementation, detachment costs are calculated using the combined labour and equipment shares only (labour + equipment share). The subcontracting share is excluded, as it represents externalised services.

$$DetachmentCosts = LabourCosts \cdot corDI \tag{A.6}$$

where:

- $DetachmentCosts$ (DC): cost of disassembly and material recovery (€)
- $corDI$: correction factor reflecting ease of disassembly based on DI

$$TransportCosts = (C_{\text{load}} \cdot t_{\text{loading}}) + (C_{\text{unload}} \cdot t_{\text{unloading}}) + (Weight_{\text{ton}} \cdot C_{\text{tonkm}} \cdot Distance) \tag{A.7}$$

where:

- $TransportCosts$ (TC): cost of transporting recovered materials (€)
- $C_{\text{load}}, C_{\text{unload}}$: loading and unloading cost rates (€/hour)
- $t_{\text{loading}}, t_{\text{unloading}}$: loading and unloading times (hours)
- $Weight_{\text{ton}}$: transported material weight (tonnes)
- C_{tonkm}: cost per tonne-kilometre (€/ton·km)
- $Distance$: transport distance (km)

$$StorageCosts = C_{\text{indoor}} \cdot \left(\frac{T_{\text{storage}}}{12}\right) \cdot (Area \cdot F_{\text{traffic}} \cdot F_{\text{stack}}) \tag{A.8}$$

where:

- $StorageCosts$ (SC): cost of storing recovered materials (€)
- C_{indoor}: indoor storage cost rate (€/m^2/year)
- T_{storage}: storage duration (months)
- $Area$: required storage area (m^2)
- F_{traffic}: factor accounting for handling space
- F_{stack}: stacking factor

A.2. Detachability Index Look-Up

Source: Alba Concepts et al. (2025)

Table A.1: Detachability Index (DI) look-up: loss share and correction factor by detachability range.

Detachability range	Loss % (%loss)	corDI factor	Description
$>$ 0.80	5%	0.8	High detachability — minimal damage
0.50–0.80	10%	1.0	Moderate detachability — some damage
0.25–0.50	40%	1.5	Low detachability — significant damage
$<$ 0.25	100%	N/A	Write-off — no residual value

The DI threshold of 0.25 operates as a binary gate: below it, RV = 0 regardless of other parameter values.

A.3. Technical Lifespan and Quality Reduction

Source: Alba Concepts et al. (2025)

The technical condition is derived from the ageing curve, which describes the change in condition as a function of a product's service life (based on NEN 2767, (Nederlands Normalisatie-instituut (NEN), 2026)):

$$C = 1 + \tfrac{1}{2}\log\left(1 - \frac{t}{L}\right) \tag{A.9}$$

where C is the technical condition score, t the age at reuse (years), and L the service life (years). The condition score is then translated into a percentage quality reduction of the total acquisition cost, as given in Table A.2.

Table A.2: Condition score to quality-reduction mapping (NEN 2767).

Score C	**Condition**	**%quality**	**Description**
1	Excellent	0%	No / very limited ageing
2	Good	10%	Minor surface wear
3	Fair	30%	Visible deterioration
4	Poor	55%	Significant deterioration
5	Bad	80%	Major structural issues
6	Unusable	100%	Technically ready for demolition

B
Case Studies

The model inputs for the case studies are derived from two distinct sources, reflecting differences in data availability and empirical grounding.

For Case Study 1, the input parameters are based on documented building specifications from WSP Nederland B.V. (2023). Structural mass, product composition, and material quantities are directly informed by reported weights and design characteristics. Where an exact match with the residual-value dataset was not available, proxy products from the dataset were selected based on the closest correspondence in mass intensity and structural function. This ensures consistency between the case-study description and the product-level residual value calculations while maintaining transparency in the assumptions.

For Case Study 2, input parameters are derived from expert elicitation (E1). The expert is familiar with both building product specifications and the residual value methodology applied in this research. Product composition, material shares, and detachability characteristics were reconstructed based on expert knowledge and aligned with the structure of the residual-value model. To ensure confidentiality, expert contributions are anonymised, and results are reported in aggregated form.

B.1. Case Study 1 Office - Final Model Input

The engineered wood variant uses glulam beams and columns and CLT floor slabs. In the reference variant, steel is used for beams and columns in the structural frame, and the floor slabs. Material use for the interior walls is the same in both cases. The engineered wood variant requires approximately 25% less total structural material mass than the steel variant, with the largest differences occurring in the floor system (−70%) and structural frame (−33%).

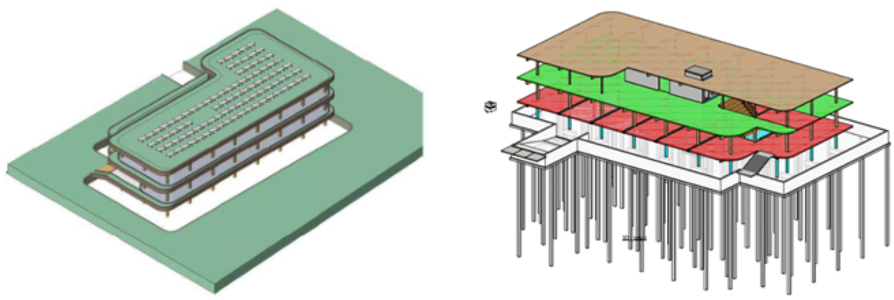

Figure B.1: Architectural design impression of the case study 1 'Office', derived from (WSP Nederland B.V., 2023)

Table B.1: Case Study 1 — final model inputs (wood and steel variants).

Element	Product specification	Quantity
Wood structure		
Floor slabs	CLT floor 200 mm	1,336 m^2
Beams + columns	Steel structure	17,422 kg
Beams + columns	Glulam beams & columns ($\frac{1}{7}$ mix)	295 m^1
Steel structure (reference)		
Floor slabs	Reinforced concrete floor 200 mm	1,336 m^2
Beams + columns	Steel structure	44,209 kg

B.1.1. Wood structure

For the CLT floor slabs, no exact match was available in the Revalto dataset because the case-study slab includes a 1% steel fraction. The model therefore uses the wood share only (99% of slab mass), giving a mass intensity of 88.4 kg/m^2. The closest dataset match is a prefabricated 200 mm CLT floor slab at 94 kg/m^2, yielding an estimated model area of 1,335 m^2; the difference from the documented floor area is small and was considered acceptable. For the glulam beams and columns, the case study does not specify exact product types, so a proxy mix was constructed from the seven glulam beam and column products in the dataset using an equal-weight average ($\frac{1}{7} \times$ product). This yields an estimated quantity of 295 m^1 for the glulam structural frame, providing a transparent and reproducible basis for linking the case-study description to the product-level residual-value dataset.

B.1.2. Steel structure - reference design

For the steel reference case, the reported floor-slab mass corresponds to 312.8 kg/m^2. The closest dataset match is a 200 mm hollow-core slab at 340 kg/m^2; applying this proxy to the same floor area gives an estimated concrete mass of 455,422 kg. This slightly heavier product was selected to avoid underestimating structural mass while keeping the input transparent and comparable.

B.2. Case Study 2 School - Final Model Input

MKC De Schatkaart is a newly built school with a gross floor area of 3,449 m^2, located in Amsterdam. The building accommodates a primary school, a daycare centre, and a sports facility intended for both the school and the surrounding neighbourhood. It is a conventionally constructed school building, comprising a steel structural frame with hollow-core slab floors. The circular design partly replaces the steel structure with glulam beams and columns, detachable hollow-core slab on the ground floor and a CLT floor for the multi level floors.

Table B.2: Case Study 2 — final model inputs (traditional and circular variants), derived from Residual Value Expert (1).

Element	Product specification	Quantity
Traditional design		
Floor slabs	Reinforced concrete floor 320 mm	3,449 m^2
Beams + columns	Steel structure	105,013 kg
Circular design		
Floor slabs	Detachable reinforced concrete floor 320 mm	889 m^2
Floor slabs	CLT upper floors 320 mm	2,710 m^2
Beams + columns	Glulam beams & columns ($\frac{1}{7}$ mix)	738 m^1
Beams + columns	Steel structure	21,003 kg

B.3. Final Model Input Dataset

Table B.3: Case Study 1 — consolidated product-level model inputs, derived from (WSP Nederland B.V., 2023).

Product	Struct.	DB (€)	Weight (kg)	%mat	%lab	DI	%qual	EC	Category
CLT floor 200mm	Wood	297,928	125,584	76%	10%	81%	0%	0.10	Bio-based
Glulam beams/columns 285m	Wood	46,610	12,095	50%	44%	81%	0%	0.10	Bio-based
Steel beams/columns 17t	Steel	87,110	17,422	44%	38%	27%	30%	2.30	Conventional
RC floor 200mm	Steel	101,536	455,442	70%	30%	16%	0%	0.90	Conventional
Steel beams/columns 44t	Steel	221,045	44,209	44%	38%	27%	30%	2.30	Conventional

Table B.4: Case Study 2 — consolidated product-level model inputs, derived via expert interviews, derived from E1.

Product	Source	DB (€)	%mat	%lab	DI	%qual	EC	Category
RC floor 320mm	CS2 Traditional	317,308	75%	25%	16%	0%	0.90	Conventional
Steel beams/columns 105t	CS2 Traditional	525,065	44%	38%	27%	30%	2.30	Conventional
CLT floor 320mm	CS2 Circular	932,240	79%	7%	81%	0%	0.10	Bio-based
Glulam beams/columns 738m	CS2 Circular	116,604	50%	44%	81%	0%	0.10	Bio-based
RC floor DfD-improved 320mm	CS2 Circular	81,730	75%	25%	25%	0%	0.90	Conventional-DfD
Steel beams/columns 21t	CS2 Circular	105,015	44%	38%	27%	30%	2.30	Conventional

C

Expert Elicitation

C.1. Expert Elicitation: Summary of Outcomes

Ten semi-structured expert interviews were conducted to test the plausibility, transmission logic, parameter assumptions, and completeness of the scenario model. Experts were selected to cover relevant domains of circular construction of Dutch public buildings — residual-value methodology, structural engineering, construction-cost estimation, material science, circular procurement, public real estate, and real-estate finance — so that each part of the model could be judged by at least one specialist. Experts are referred to here as E1–E10 and their domains of expertise are listed in Table C.1.

Table C.1: Expert panel by primary domain of expertise (anonymised).

Code	Primary domain
E1	Financial Residual Value Building Products
E2	Contracting - Steel Reuse
E3	Circular Construction policy - EU/NL
E4	Construction Costs and Data
E5	Public buildings - Residual Value and Circular Procurement
E6	Material science - Concrete and Steel
E7	Sustainability Construction Cost Avisory
E8	Public buildings - Circular Procurement and Reuse Policy
E9	Real-estate Finance
E10	Structural Engineering

C.1.1. Scenario Plausibility

The baseline and transition scenarios were judged directionally plausible but politically contingent. Experts engaging with the policy scenarios (E1, E2, E3, E4, E5, E6) accepted the direction of travel, a rising carbon price and a falling labour-tax, while consistently questioning the magnitude and the national political will behind the labour-tax shift. An expert validated the social contribution and underlying logic of the labour-tax shift, illustrating this with a project in which reused materials were applied and workers with a distance to the labour market were employed under reduced labour taxation (E9). Several judged the carbon-price assumptions used during elicitation (€75–250/tonne) to be conservative relative to PBL and European Commission projections (E1, E3), which informed the subsequent upward revision of the carbon-price trajectory in the final model. The labour-tax shift was viewed as the more radical and less institutionally anchored of the two, with the EU pathway (CBAM, ETS) seen as a more likely driver of change than national fiscal reform (E1, E3).

The initial carbon-price assumptions were considered conservative (E3, E7) leading to the adoption of the highest benchmark values from the PBL and European Commission guidelines. Labour tax reduction rates were not contested in principle; however, because the Ex'Tax concept is less widely established than carbon pricing, the labour-tax reduction trajectory remains under-researched and scenario data are scarce at both the European and national scale. No scenario data were identified beyond the Copper8 (2022) project.

C.1.2. Transmission Logic

The expert elicitation assessed the plausibility, validity, and completeness of the modelling assumptions. Overall, the interviews supported the central logic of the scenario model, particularly the expectation that labour tax reduction would have a stronger direct effect on residual value than carbon pricing under current Dutch conditions, a pattern noted by multiple experts. Experts also noted that an increase in direct building costs due to carbon pricing does not translate into higher labour costs, which in the original formula would otherwise be affected. Experts who assessed the causal chain (E1, E2, E3, E4, E5, E6) agreed that a labour-tax reduction lowers the labour share and raises the material share, and that carbon pricing raises direct building cost and thereby the material-value base, without acting directly on labour-based detachment costs. Independently of one another, several experts anticipated that the labour-tax effect would exceed the carbon-price effect (E1, E3, E4, E7), the pattern the model subsequently produced, and noted that this gap partly reflects the conservative carbon price. One structural caveat recurred: carbon pricing applied uniformly does not, on its own, reward detachability, since disassemblable and non-disassemblable products face the same surcharge (E2). This supported treating detachability as a separate design instrument rather than a price-driven outcome.

C.1.3. Assumption Validation

The base-model parameters were broadly supported, with targeted refinements. Experts confirmed the residual-value formula structure and the material-share, labour-share, and embodied-carbon inputs (E1, E3, E7). Three correction factors were challenged as optimistic: storage duration (six months was judged too short against real durations of up to two years, E2), revision costs (a zero default was considered unrealistic, E2, E3, E7), and the conservatism introduced by excluding inflation (E1, E9). The decision to cap the reinforced-concrete floor's detachability index was reinforced by warnings that concrete reuse is highly system-dependent and easily overstated (E6, E10). Biogenic carbon storage in timber was flagged as outside the model boundary and recommended for explicit treatment in the sensitivity analysis (E3, E6, E7). The assumption of zero revision costs (RC = 0%) was challenged: experts emphasised that inspection, certification, and reprocessing generate non-negligible costs. This prompted sensitivity ranges for revision-related parameters, testing whether 5% or 10% would be more reasonable under current conditions.

Experts also indicated that storage costs may be both under- and overestimated, because actual storage durations often exceed the model assumption of six months. This prompted sensitivity ranges for storage-related parameters, with 12 months (Expert 2) or 0 months (Expert 8) suggested as alternatives. Experts noted the theoretical residual value calculation remains conservative overall because inflation is not incorporated (E1, E9).

Detachability was repeatedly confirmed as a critical determinant of residual value. In the first interviews, a causal relationship between the price instruments (labour tax, carbon pricing) and improvements in detachability was not supported. Specialists further indicated that the baseline detachability data were likely conservative: the steel structure has a minimum DI of 0.27, while for concrete, detachability is highly system-dependent and can vary substantially where specific mechanical connection systems are used. The same experts noted, however, that highly specific mechanical connections for concrete are not easily reusable owing to their design uniqueness. For the hollow-core concrete floor, Expert 10 warned that assuming substantially improved detachability would overestimate practical reuse potential, because concrete elements can become highly specific and therefore difficult to reapply in future projects.

C.1.4. Model Validation and Completeness

The completeness check surfaced barriers consistently identified as outside the model's scope rather than flaws within it. The most frequent were the immaturity of secondary-material markets and supply–demand matching (E2, E6, E7, E8, E9, E10), the absence of material-passport and documentation data (E2, E4, E9), storage and logistics constraints in the densely built Dutch context (E2, E6, E7), and the temporal mismatch between long-term residual value thinking and short-term budgets (E5, E9, E10).

Persistent perception barriers, that reused materials are inherently riskier or lower quality, were raised as a trust gap (E9, E10). Several experts independently noted designing with available, recoverable materials (E5, E8). These mechanisms were taken to confirm that the model captures the dominant financial transmission pathway while remaining, by design, silent on the market and informational conditions under which modelled value is realised. Expert interviews with municipal building commissioners validated circulation depreciation to enhance circular depreciation, as a way of reallocating the freed room, toward maintenance and monitoring, so recognised material value can be tracked and claimed at end-of-life, or toward procuring and desigining with more detachable and biobased products

C.2. Expert Interviews Summaries

E1 — Financial Residual Value Building Products

Function	Coded outcome
Scenario plausibility	Baseline carbon price realistic; labour-tax shift logical but low national political traction. €250/tonne by 2050 possibly too low. EU pathway (CBAM, ETS) seen as more likely driver than national policy.
Transmission logic	Full agreement with the τ_L and carbon-price chains. τ_L judged substantially more impactful than carbon pricing. Noted if carbon pricing should target reused (vs. new) products, and how this translates to residual value.
Assumption validation	Agreed with base parameters and formula structure. Noted the estimate is conservative because inflation is excluded.
Model validation	Identified political inertia (Ex'Tax proposals have been around quite long) and absence of a transaction-data marketplace for valuers and accountants as factors outside the model.

E2 — Contracting - Steel Reuse

Function	Coded outcome
Scenario plausibility	New material judged "too cheap"; raising material price and lowering labour cost would favour reuse. Significant market change expected within two years, visible by 2030.
Transmission logic	τ_L confirmed as more impactful for labour-intensive reuse. Carbon pricing does not reward detachability unless price is differentiated between detachable and non-detachable products.
Assumption validation	Storage duration underestimated (six months vs. up to two years in practice); revision cost of 0% unrealistic.
Model validation	Documentation/data availability (drawings, 3D models, known supplier) should be an explicit variable. Named specific revision costs such as contamination testing (chromium-6) for steel, and municipal storage hubs as enablers.

E3 — Circular Construction Policy - EU/ NL

Function	Coded outcome
Scenario plausibility	Starting point plausible; recommended verification against PBL and European Commission scenario tables. EC scenarios sometimes exceed €250/tonne, so assumptions may be conservative. Flagged the ETS1 (materials) vs. ETS2 (building energy) distinction as critical.
Transmission logic	Agreed; carbon pricing primarily hits new material, with no automatic pass-through to transport, storage, or detachability. τ_L greater than carbon pricing, consistent with the conservative carbon price.
Assumption validation	Revision costs not zero and often underestimated; transport costs may fall as the secondary market becomes more efficient. Biogenic carbon storage in wood falls outside scope and should be stated as a limitation.
Model validation	Labour-tax feasibility "remains uncertain" but a "radical and interesting" shift if implemented. Reused steel increasingly accepted; certification improving.

E4 — Construction Costs

Function	Coded outcome
Scenario plausibility	– (interview focused on cost parameters)
Transmission logic	Labour tax has a larger effect than carbon pricing; carbon effect is material-specific (steel $>$ concrete $>$ wood).
Assumption validation	Weight is the determining factor (mass governs load before volume). Per-kilogram comparison misleading without building-level normalisation; concrete may need larger cross-sections; fewer concrete benchmarks than steel.
Model validation	Construction-cost knowledge underrepresented in the transition debate; the financial picture is often decisive. Noted lower labour rates must account for productivity and supervision needs.

E5 — Public Buildings - Residual Value and Circular Procurement

Function	Coded outcome
Scenario plausibility	Financial incentives necessary to accelerate the transition, but municipalities lack resources and perceive circular choices as riskier. Direction inevitable ("not if but when"); groundwork must be laid now for buildings harvested in 40–50 years.
Transmission logic	Both instruments work in the same direction; financial incentives accelerate development. Could not confirm whether carbon pricing should affect the labour component of detachment cost.
Assumption validation	Percentage loss stays constant while absolute loss rises with value. Wood preferred for carbon reasons, with additional advantages.
Model validation	Identified residual-value recognition, circular depreciation, certification, and procurement requirements as key instruments to circular construction. Barriers: certification/permits, split maintenance responsibility, insufficient national funding.

E6 — Material science - concrete and steel

Function	Coded outcome
Scenario plausibility	CBAM viewed positively as partial protection, with a caveat on export exposure; emphasised the need for policy predictability for industrial planning.
Transmission logic	– (labour-tax shift unfamiliar to this expert; focus on carbon pricing ETS/CBAM). Carbon pricing effect on Direct Building Costs validated.
Assumption validation	Multiple material streams on a demolition site are a logistical challenge in the densely built Netherlands. Noted limited domestic wood supply for large-scale structural use.
Model validation	Insufficient material available to reuse at scale; prefab factories not set up for modularity (20–30-year depreciation cycles); new material “too cheap”; certification adds significant cost; demand-side gap among architects, clients, and developers.

E7 — Sustainability Cost Advisory

Function	Coded outcome
Scenario plausibility	Policy alone insufficient; system conditions required (storage, standardisation, modularity, regulation, logistics, contractor capability, demand certainty).
Transmission logic	Agreed carbon pricing does not directly affect detachment cost (labour-based) and increases value through the material-value term. If $\tau_L \gg$ carbon pricing, the carbon price may be set too conservatively.
Assumption validation	Simplified treatment acceptable for an exploratory model but can matter greatly for heavy materials (concrete). Wood historically reused; biogenic carbon should be sensitivity-tested.
Model validation	Theoretical residual value $\neq$ realised value; hidden design/coordination costs not captured; storage and standardisation gaps; client ambition and aesthetic expectations drive demand.

E8 — Public buildings - Circular Procurement and Reuse

Function	Coded outcome
Scenario plausibility	–
Transmission logic	–
Assumption validation	–
Model validation	Priority should be less demolition, maximum reuse, or not building at all; government must be exemplary in both safety standard and circularity. Unpredictable material flow and difficult supply–demand matching; expensive storage; complex, costly dismantling; unclear risk allocation. Endorsed circular depreciation to residual value, not €0, and designing with available materials. Attention to wood; geographic price variation significant (wood cheaper across the German border).

E9 — Real-estate Finance

Function	Coded outcome
Scenario plausibility	Current system prioritises present value; future value of reusable components unaccounted in financing. Labour subsidies or secondary-material tax reductions were identified as mechanisms to correct this imbalance by improving the business case for circular, labour-intensive activities. Validated this through a project example in which disassembly and material recovery were successfully implemented using workers with a distance to the labour market, supported by reduced labour taxation. Rising carbon costs improve the relative position of reused material.
Transmission logic	Carbon pricing affects materials not labour; value increases through the material-value term. Both instruments work together; cautioned against simplistic material substitution.
Assumption validation	Structural engineered wood products perform well, biobased materials should be applied when appropriate.
Model validation	Data-infrastructure gaps (material passports, databases); persistent perception that new is safe and reused is suspect; temporal mismatch between long-term value and short-term optimisation. Recommended certification, quality labels, and product banks.

E10 — Structural Engineering

Function	Coded outcome
Scenario plausibility	Market forces alone unlikely to internalise long-term residual value
Transmission logic	Policy and financial incentives essential; coordinated technical and governance approaches needed.
Assumption validation	CLT/HSB systems associated with lower structural weight and foundation loads, and potentially higher long-term residual value. Residual value conditional on moisture protection and verified remaining service life.
Model validation	Current valuation methods do not recognise future material value; foundation elements offer limited reuse despite high embodied carbon; confidence in future reuse markets lacking, Recommended bolted/standardised connections, and design for dissesambly.

C.3. Expert Elicitation Building Product Data Model Input

The first six columns capture the initial dataset values; the final column records the expert-elicitation outcome, distinguishing the baseline parameterisation from subsequent confirmation, refinement, or unresolved uncertainty.

Table C.2: Initial model input values and expert-elicitation outcomes for beams, columns, and floor slabs.

Building part (NL SfB)	Material	Method	%Lab	%Mat	Initial DI	EE outcome
Floor	Concrete	Prefab	30%	70%	0.17	Adjusted to 0.16
Floor	Wood (CLT)	Prefab	10%	76%	0.72	Adjusted to 0.81, if no wet screed is applied
Structural frame	Concrete	Prefab	38%	74%	0.29	Confirmed; 0.46 may apply for mechanically connected systems
Structural frame	Steel	Prefab	38%	44%	0.13	Expert indicated a minimum of 0.27
Structural frame	Wood	Prefab	44%	50%	0.76	Adjusted to 0.81

D

Scenario and Sensitivity Analysis

D.1. Price based Effects - DfD-0

Table D.1: CS1 wood structure — residual value by scenario, DfD-0 (€).

Wood structure	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total $\triangle$RV
τ_L effect	158,884	162,234	169,306	175,758	16,873
p_{CO_2} effect	158,884	159,378	160,707	162,321	3,437
$\tau_L + p_{CO_2}$ effect	158,884	162,732	171,182	179,356	20,472

Table D.2: CS1 steel structure — residual value by scenario, DfD-0 (€).

Steel structure	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total $\triangle$RV
τ_L effect	$-93{,}015$	$-89{,}588$	$-82{,}354$	$-75{,}755$	17,260
p_{CO_2} effect	$-93{,}015$	$-92{,}572$	$-91{,}378$	$-89{,}928$	3,087
$\tau_L + p_{CO_2}$ effect	$-93{,}015$	$-89{,}137$	$-80{,}619$	$-72{,}370$	20,645

Table D.3: CS2 traditional design — residual value by scenario, DfD-0 (€).

Traditional design	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total $\triangle$RV
τ_L effect	$-220{,}946$	$-212{,}806$	$-195{,}622$	$-179{,}946$	41,000
p_{CO_2} effect	$-220{,}946$	$-219{,}894$	$-217{,}056$	$-213{,}613$	7,333
$\tau_L + p_{CO_2}$ effect	$-220{,}946$	$-211{,}734$	$-191{,}501$	$-171{,}907$	49,039

Table D.4: CS2 circular design — residual value by scenario, DfD-0 (€).

Circular design	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total $\triangle$RV
τ_L effect	663,460	670,890	686,574	700,882	37,422
p_{CO_2} effect	663,460	670,361	688,971	711,554	48,094
$\tau_L + p_{CO_2}$ effect	663,460	677,839	712,653	750,711	87,250

D.2. Price Based Effects - DfD-1

Compared with the DfD-0 results in Section D.1, the combination of labour tax and carbon pricing under improved detachability shows that carbon pricing now exerts a larger effect on the increase in residual value.

Table D.5: CS1 wood structure — residual value by scenario, DfD-1 (€).

Wood structure	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total △RV
Labour tax only	188,443	191,677	198,506	204,736	16,293
Carbon price only	188,443	189,111	190,911	193,096	4,653
Combined	188,443	192,353	201,066	209,668	21,225

Table D.6: CS1 steel structure — residual value by scenario, DfD-1 (€).

Steel structure	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total △RV
Labour tax only	18,618	23,683	34,377	44,133	25,516
Carbon price only	18,618	25,193	42,926	64,444	45,827
Combined	18,618	30,329	59,503	92,456	73,838

Table D.7: CS2 traditional design — residual value by scenario, DfD-1 (€).

Traditional design	S0 (2026)	S1 (2030)	S2 (2040)	S3 (2050)	Total △RV
Labour tax only	164,421	177,484	205,061	230,218	65,797
Carbon price only	164,421	192,663	268,830	361,257	196,836
Combined	164,421	205,963	312,204	435,401	270,980

Table D.8: CS2 circular design — residual value by scenario, DfD-1 (€).

Circular design	S0	S1	S2	S3	Total △RV
Labour tax only	699,094	706,385	721,776	735,817	36,723
Carbon price only	699,094	706,205	725,383	748,654	49,560
Combined	699,094	713,549	748,679	787,253	88,159

D.3. Residual Value to Investment Ratio (RV/DB)

Table D.9: Direct building costs versus residual value by structure under DfD-0 (base detachability).

	Direct building cost (€)			Residual value (€)		RV/DB (%)	
Structure	2026	2050	Δ	2026	2050	2026	2050
Wood Structure	431,648	460,721	29,073	158,884	179,356	36.8	38.9
Steel Structure	322,581	598,834	276,253	−93,015	−72,370	−28.8	−12.1
Traditional Design	842,373	1,927,068	1,084,695	−220,946	−171,907	−26.2	−8.9
Circular Design	1,235,589	1,490,931	255,342	663,460	750,711	53.7	50.4

Table D.10: Direct building costs versus residual value by structure under DfD-1 (improved detachability).

Structure	Direct building cost (€)			Residual value (€)		RV/DB (%)	
	2026	2050	Δ	2025	2050	2025	2050
Wood Structure	431,648	460,721	29,073	188,443	209,668	43.7	45.5
Steel Structure	322,581	598,834	276,253	18,618	92,456	5.8	15.4
Traditional Design	842,373	1,927,068	1,084,695	164,421	435,401	19.5	22.6
Circular Design	1,235,589	1,490,931	255,342	699,094	787,253	56.6	52.8

D.4. Sensitivity Analysis

All parameters are swung around the nominal base residual value; the inflation row is the exception, swung around the inflation-adjusted base (at 3.3% compounded over 24 years), so that its range reflects rate uncertainty rather than the one-off compounding level shift.

Table D.11: Parameter low/base/high values used in the one-at-a-time (OAT) sensitivity analysis, for the CLT floor and the steel structure. Continuous parameters are varied by $\pm 20\%$ around the base; correction factors move between discrete detachability or quality bands; revision cost is stress-tested from zero.

ID	Parameter	Driver	CLT Floor			Steel Structure			Swing type
			Low	Base	High	Low	Base	High	
Correction factors									
CF1	Loss	%loss	10%	5%	0%	100%	40%	10%	Lookup (discrete)
CF2	Quality reduction	%quality	30%	0%	0%	55%	30%	0%	Lookup (NEN 2767)
CF3	Detachability corr. factor	corDI	1.00	0.80	0.80	1.50	1.50	1.00	Lookup (discrete)
CF4	Revision cost	%rev	0%	5%	10%	0%	5%	10%	Stress test
CF5	Transport cost	d (km)	50	100	200	50	100	200	Two-sided range
CF6	Storage cost	T_{sc} (mo)	0	6	12	0	6	12	Two-sided range
Carbon price									
P1	Embodied carbon (CLT)	EC_{CLT}	0.08	0.10	0.12	0.08	0.10	0.12	$\pm 20\%$
P2	Embodied carbon (steel)	EC_{Steel}	1.84	2.30	2.76	1.84	2.30	2.76	$\pm 20\%$
P3	CO_2 price (€/t)	$p_{\mathrm{CO_2}}$	248	310	372	248	310	372	$\pm 20\%$
P4	Direct building cost	DB	-20%	0	$+20\%$	-20%	0	$+20\%$	$\pm 20\%$
Labour tax									
P5	Material share	%mat	-20%	0	$+20\%$	-20%	0	$+20\%$	$\pm 20\%$
P6	Labour share	%lab	-20%	0	$+20\%$	-20%	0	$+20\%$	$\pm 20\%$
P7	Labour tax wedge	τ_L	16.8%	21.0%	25.2%	16.8%	21.0%	25.2%	$\pm 20\%$
Macroeconomic									
P8	Annual inflation rate	i	2.64%	3.30%	3.96%	2.64%	3.30%	3.96%	$\pm 20\%$

Table D.12: CLT floor: one-at-a-time sensitivity results.

Rank	Parameter	Driver	Low	High	RV low	RV base (€)	RV high	Δ low	Δ high (€)	Max |ΔRV|
1	Quality reduction	%quality	30%	0%	117,664	190,015	190,015	$-72{,}351$	0	72,351
2	Annual inflation rate	i	2.64%	3.96%	355,130	414,187	482,591	$-59{,}056$	68,404	68,404
3	Material share	%mat	-20%	$+20\%$	146,375	190,015	233,656	$-43{,}640$	43,640	43,640
4	Direct building cost	DB	-20%	$+20\%$	151,800	190,015	228,230	$-38{,}215$	38,215	38,215
5	Loss	%loss	10%	0%	178,531	190,015	201,500	$-11{,}484$	11,484	11,484
6	Disassembly cost	corDI	1.00	0.80	183,938	190,015	190,015	$-6{,}078$	0	6,078
7	Labour share	%lab	-20%	$+20\%$	194,877	190,015	185,153	4,862	$-4{,}862$	4,862
8	Labour tax wedge	τ_L	16.8%	25.2%	194,877	190,015	185,153	4,862	$-4{,}862$	4,862
9	Transport cost	d (km)	50	200	191,058	190,015	187,931	1,042	$-2{,}085$	2,085
10	Embodied carbon (CLT)	EC_{CLT}	0.08	0.12	189,452	190,015	190,578	-563	563	563
11	CO_2 price	$p_{\mathrm{CO_2}}$	248	372	189,452	190,015	190,578	-563	563	563
12	Storage cost	T_{sc} (mo)	0	12	190,048	190,015	189,950	33	-65	65
13	Revision cost	%rev	0%	10%	190,015	190,015	190,015	0	0	0
14	Embodied carbon (steel)	EC_{Steel}	1.84	2.76	190,015	190,015	190,015	0	0	0

Table D.13: Steel structure: one-at-a-time sensitivity results.

Rank	Parameter	Driver	Low	High	RV low	RV base (€)	RV high	Δ low	Δ high (€)	Max |ΔRV|
1	Loss	%loss	100%	10%	$-161{,}408$	$-94{,}731$	$-61{,}392$	$-66{,}677$	33,339	66,677
2	Disassembly cost	corDI	1.50	1.00	$-94{,}731$	$-94{,}731$	$-53{,}064$	0	41,667	41,667
3	Quality reduction	%quality	55%	0%	$-123{,}902$	$-94{,}731$	$-59{,}725$	$-29{,}171$	35,006	35,006
4	Annual inflation rate	i	2.64%	3.96%	$-177{,}048$	$-206{,}490$	$-240{,}592$	29,442	$-34{,}102$	34,102
5	Labour share	%lab	-20%	$+20\%$	$-69{,}731$	$-94{,}731$	$-119{,}731$	25,000	$-25{,}000$	25,000
6	Labour tax wedge	τ_L	16.8%	25.2%	$-69{,}731$	$-94{,}731$	$-119{,}731$	25,000	$-25{,}000$	25,000
7	Direct building cost	DB	-20%	$+20\%$	$-75{,}274$	$-94{,}731$	$-114{,}187$	19,456	$-19{,}456$	19,456
8	Material share	%mat	-20%	$+20\%$	$-101{,}065$	$-94{,}731$	$-88{,}396$	$-6{,}334$	6,334	6,334
9	Revision cost	%rev	0%	10%	$-93{,}064$	$-94{,}731$	$-96{,}398$	1,667	$-1{,}667$	1,667
10	Embodied carbon (steel)	EC_{Steel}	1.84	2.76	$-95{,}521$	$-94{,}731$	$-93{,}940$	-791	791	791
11	CO_2 price	$p_{\mathrm{CO_2}}$	248	372	$-95{,}521$	$-94{,}731$	$-93{,}940$	-791	791	791
12	Transport cost	d (km)	50	200	$-94{,}364$	$-94{,}731$	$-95{,}465$	367	-734	734
13	Storage cost	T_{sc} (mo)	0	12	$-94{,}682$	$-94{,}731$	$-94{,}779$	49	-49	49
14	Embodied carbon (CLT)	EC_{CLT}	0.08	0.12	$-94{,}731$	$-94{,}731$	$-94{,}731$	0	0	0